WASTE AND WASTE MANAGEMENT

Waste Management

Strategies, Challenges and Future Directions

Nanda Gopal Sahoo, PhD
Editor

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PREFACE

The management of waste is a very sensitive and a burning issue which is affecting everyone all over the globe. With the sudden advent of globalization, urbanization, and the massive change in lifestyle, the amount of waste generated has increased to an extent never seen before. Such an increase has come with threatening consequences. To make human life easier and more comfortable, a number of innovations have been introduced in recent years, such as development of plastics goods and electronic items, which have led to an exponential growth in e-waste, medical and plastics wastes. Most of the agriculture, forest and food wastes are untreated and unutilized, and as such these are burned, mismanaged and dumped in landfills. This has endangered our ecosystem, polluted water bodies and caused ecological imbalance in the biosphere. Overall, these wastes and human habits are spoiling the beauty of our planet and polluting fresh water sources, the sea and the overall environment. We all know that most waste is treated through burning which leads to the generation of harmful gases and affects living organisms and our environment. These gases are creating a film over the earth's surface, trapping heat and preventing its escape, thus causing soaring temperatures and eventually global warming. To overcome this situation, many futile efforts have been made by scientific and environmentalist communities and municipal bodies to no avail. Besides this, a larger part of waste is dumped into the seas without any necessary primary treatment which poses a grave threat to aquatic life. Thus, there is a great need for efficient scientific waste management approaches as well as advanced technology that can convert the waste into value added products. There are many techniques and ways to tackle this waste but more research and development in this area is still required to achieve desired results.

This book explores a new aspect of managing waste and developing efficient technology to convert this waste into value added products. It briefly provides the recent survey, challenges, and advancements in waste management technologies and gives direction for future planning. It also provides cutting edge knowledge on classification and management of waste, recycling and upcycling of waste into value added products or carbon nanomaterials, utilization of waste towards to enhancing the global economy, role of microorganism for the treatment of waste, role of nanotechnology in waste treatment and water purification, management of E-waste and biomedical waste as well as how we can plan for the future to manage waste. This book is organized in such a way as to give the reader a clear and concise thought regarding waste management and converting it into value added products. This book will emerge as the reference guide that overviews up to date literature in the field of waste and its management, challenges, converting technology and future possibilities.

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Finally, this book is a complete information package for students, professors, scientists, industries and R&D; those who are working in the field of waste management and its converting technologies.

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Chapter 1

SUSTAINABLE MANAGEMENT OF WASTE: PRESENT CHALLENGES AND FUTURE PLANNING

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ABSTRACT

Exponential waste generation is one of the major issues in the 21st century around the world. Though there are many improvements and innovations globally, there is still a lack of urgent action to deal with it sustainably. Due to the problem arising from simultaneous growth in population, economic competition, and environmental challenges from air pollution to the scarcity of water to higher cost of energy for domestic lives, planning is necessary for a better future. This chapter presents a detailed account of challenges associated with waste that have a high impact on the environment and public health, current waste generation trend, collection, and disposal scenario globally, along with the regulatory and institutional framework. The current waste management system focuses mainly on short-term impact and end-of-pipe solutions, which may be reactive but fail to promote sustainability. Here is the need for integrated waste management methodologies for attaining sustainable development goals. It includes strategy development based on current complex challenges and implications of rules which transcend traditional land-filling for waste disposal. Our priority is to move towards a circular economy approach in waste management by utilizing resources within the waste. Sustainable waste management includes four essential tools: waste reduction, reuse, recycling, and recovery. Waste segregation at source and resource recovery are critical concerns for efficient waste management of modern researchers. This chapter also includes emerging cost-effective waste utilization technologies for recycling waste and recovery of resources and energy. Sustainability can only be achieved if trash gets beneficial revenue. Thus, planning and approaches are based on three "E's" – economy, environment, and equity. Regardless of sustainable planning and strategies, updating existing setup or technologies for remediation is only the first step in a much larger

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process. The success solely relies upon the adaption and engagement of the whole community like governments, residents, businesses, and civic organizations.

Keywords: sustainable planning approaches, integrated waste management methodologies, waste to energy, circular economy

1. INTRODUCTION

Waste management is an efficient utility service as well as a critical component for a sustainable future. But unfortunately, the realization of its resource value is still unidentified. The more disturbing thing is that the available and reliable data on waste statistics are severely lacking. The Global Waste Management Outlook (GWMO) estimates total waste is 7 to 10 billion tonnes per year, including household, commerce, industry, and construction (United Nations Environment Programme 2016). The municipal solid waste contribution is around 2 billion. Thus, it deserves maximum attention because of its multiple negative environmental impacts, including greenhouse gas emissions, ocean plastic accumulation, metal contamination via leaching, etc. An exponential increase in population, industrialization, and urbanization results in the generation of the enormous waste heap. The main question arises: What should be the cost of inaction of waste management (Wilson and Velis 2015). It must deteriorate the environment with uncontrolled waste generation and disposal, open burning, flood damage, and many more. Most importantly, it will hamper public health and other living species. 2 billion people still lack a proper waste collection facility worldwide. The GWMO also estimates that the cost of inaction is 5-10 times greater than the sustainable waste management cost (Wilson and Velis 2015). Similar to solid waste management, wastewater treating facility is not in better shape. More than 2 million people are dying each year due to the scarcity of fresh drinking water worldwide. The increase in population trend will reach 9 billion in 2050 from the current 7 billion world's population. Therefore, it is high time to take care of waste management matter in a sustainable manner.

The current waste management systems are mainly based on the end-of-pipe solution that is not efficient enough to attain sustainability. Though there has been significant progress over the decades recently still worldwide acceptability is necessary. The main focus should be on the governance system to look after the waste management that happens in practice. For that, holistic approaches are required. This chapter deals with the sustainable planning approach both the ways qualitatively and quantitatively. We tried to present the latest available data of waste collection, treatment, and disposal trends on a global scale for both solid and liquid waste to achieve successful planning. Integrated waste management methodologies will help upgrade existing waste assessment tools by expressing social, environmental, and economic pathways for better forecasting waste management and decision-making. Waste-to-energy is a new emerging technological approach in the context of effective waste utilization of valuable resources. This chapter also includes sustainable technologies that lead to value-added products without hampering the "go green" concept. Future planning for sustainable waste management is only the first step of a much larger process. The way forward is much beyond setting a goal to urgent action in reality.

2. Global Scenario of Waste Management

2.1. Waste Generation Volume

Waste generation is the natural reflection of rapid industrialization, population growth, increasing urbanization, and rising demand for everyday living. Based on the latest data available on an average of 0.74 kilograms of waste generated per capita per day worldwide, the rate thoroughly varied from 0.11 to 4.54 kilograms per capita per day by individual countries (Kaza et al. 2018). Currently, countries from East Asia and the Pacific contribute a significant portion of the world's waste of 23%, followed by Europe and Central Asia of about 20% of the total magnitude of waste (Figure 1). The countries from North Africa and the Middle East region contribute the least proportion to only 6%. The other countries from South Asia, North America, Latin America, the Caribbean, and Sub-Saharan Africa share 17%, 14%, 11%, and 9% of the world's waste.

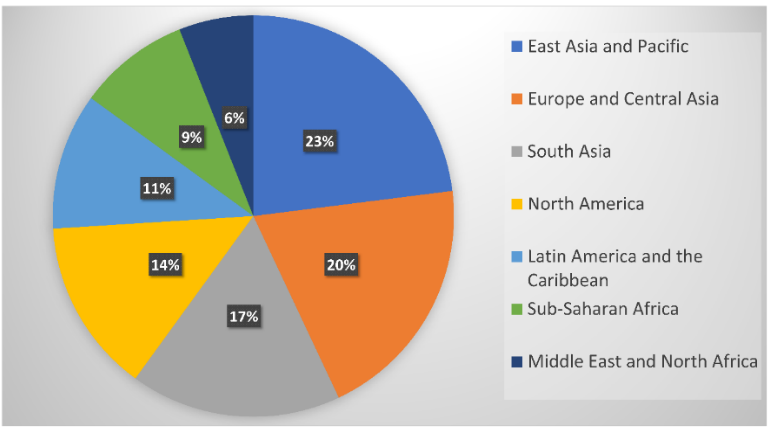

Figure 1. Share of waste generated by region percent (Data from (Kaza et al. 2018)).

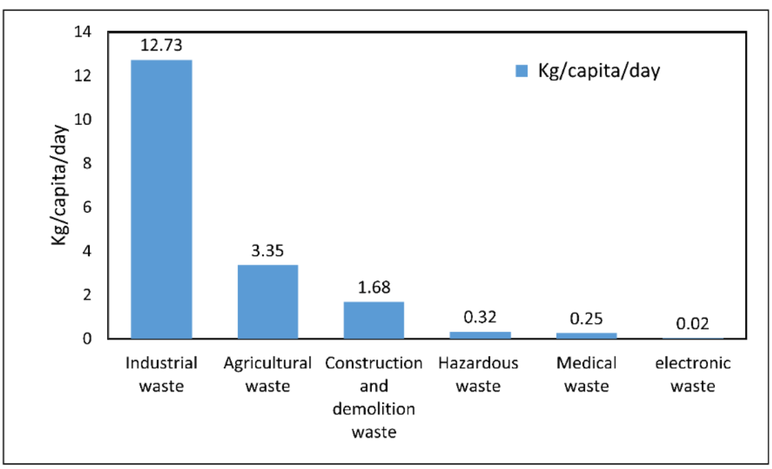

Figure 2. Average solid waste generation on per day basis (Data from (Kaza et al. 2018)).

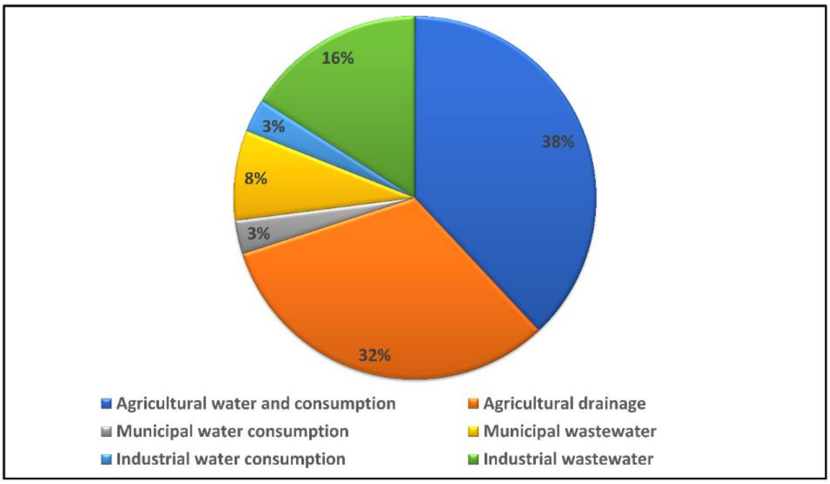

Figure 3. Global consumption of water and wastewater generation by primary water use sector (circa 2010) (Data from (WWAP 2017)).

Solid waste originates from different sources like municipal, industrial, agricultural, mining, and domestic activities. According to the World Bank, the global annual waste generation will increase to 70% by 2050 if the current trend persists (Kaza et al. 2018). It was estimated that 2.01 billion tonnes of municipal solid waste were generated in 2016, increasing to 3.40 billion tonnes by 2050 (Kaza et al. 2018). Apart from municipal waste, other major waste streams, including industrial, agricultural, medical, and electronic, also contribute to the global solid waste generation. The proportion of different solid wastes in kg/capita/day has been given in Figure 2 (Kaza et al. 2018).

Like solid waste generation, appropriate data for wastewater generation is grossly lack worldwide. Approximately 80% of wastewater is discharged into the environment openly or after little treatment (UN-Water 2015). The statistical data covering all three aspects of wastewater generation, treatment, and use was only available for 55 out of 181 analyzed countries (Sato et al. 2013). Moreover, it was found to be only one-third of the countries (37%) that fall under current categories from 2008 to 2012. According to the AQUASTAT database of the Food and Agriculture Organization (FAO) of the United Nations, freshwater withdrawal is at a rate of 3,928 km^3 per annum globally, out of which agricultural, municipal, and industrial water consumption is 1,716 km^3 per year (around 44%). The remaining 56% is released into the environment as wastewater is shown in Figure 3.

Waste generation has a positive relationship with the economic development of the country. The waste generation rate is proportional to the income levels and urbanization rate of a nation. Also, it is important to note that the waste generation growth rate is the least for high-income countries as they have already reached the peak of economic development. Still, the growth rate will be higher for medium- and low-income countries.

2.2. Waste Management Methods

Waste collection service is generally provided at the municipal level in urban areas. There are several waste collection service models across the world. Like waste generation, high-and low-income countries follow the same trend for waste collection and disposal practices. Solid waste collection rates in high-income countries and North America are almost 100% (Kaza et al. 2018). The rate decreases for upper-middle-income (82%), lower-middle-income (51%), and low-income (39%) countries. A similar trend is also followed for wastewater treatment by the income level of the region. High-income countries treat wastewater about 70% of their generation, whereas upper-middle-income and lower-middle-income countries treat 38% and 28%, respectively (Sato et al. 2013). It is found to be only 8% for low-income countries. The global solid waste treatment and disposal percentage show around 37% of it go to land-fill (specified and unspecified), 19% for recycling and composting, 11% for modern incineration, and 33% still account for open dumping (figure 4) (Kaza et al. 2018). Based on reported data from the World Bank, due to open dumping and disposal practices without any appropriate land-fill gas capture systems, CO_2 emissions contribute to 5% of total global emissions in 2016.

Many developing countries or low-income countries don't have accurate data for the generation of waste and its disposal capacities. In India, 1.4 lakh tonnes of wastes are generated daily, including dry, wet, and plastic waste. Despite taking measurable steps of segregation at source, composting, recycling, and reusing, the procurement of waste is a worrisome problem in India. Especially for hazardous waste, which is of the amount of 74.6lakh tonnes annually. As of 2017, India collected 91% of total municipal solid waste generated, treated only 23%, and the remaining amount went to land-fill. The Associated Chambers of Commerce of India (ASSOCHAM) and PricewaterhouseCoopers (PwC) studied that 10- 15% of industrial waste is hazardous and stated increasing at a rate of 2 to 5% per year. Currently, it is of global concern to find socioeconomic management to clean the environment for sustainable development. The waste management cycle can be broadly classified into four major parts (i) Prevention or segregation of polluting element at its source, (ii) Recycling the waste with minimal environmental impact, (iii) Reuse it after treatment, (iv) Recovery of resources from waste.

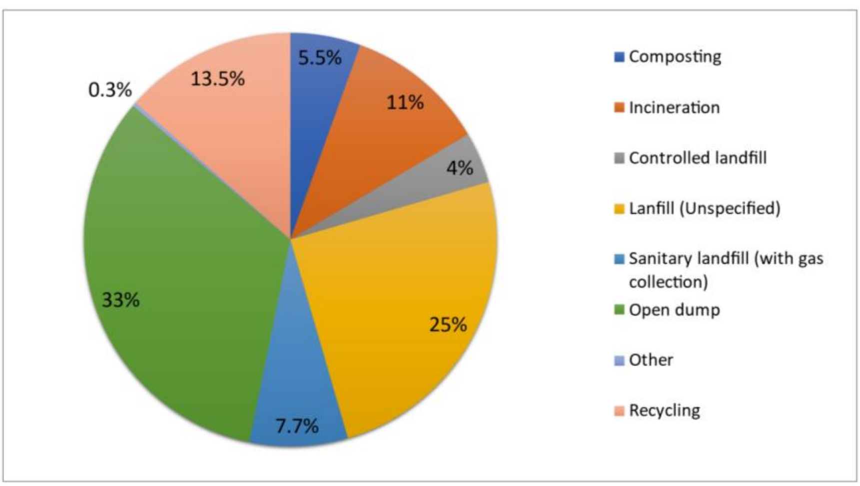

Figure 4. Global treatment and disposal of waste (Data from (Kaza et al. 2018)).

2.3. Present Regulation for Waste Management

A set of laws was passed in the United States between the 1960s and 1990s to protect the environment (Rosa et al. 2016; Johnson and Lichtveld 2017). The Resource Conservation and Recovery Act (RCRA) in 1976 was established to regulate solid and hazardous waste. It was an amendment of the Solid Waste Disposal Act, 1965, applicable only for solid and non-hazardous waste (Rosa et al. 2016). The RCRA set the standard for waste generation, hazardous waste management, transportation, storage, disposal. Another important law is the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, also known as Superfund), established in 1980 and amended in 1986 (Rosa et al. 2016). The Superfund states that chemical and petroleum industries have to pay tax on releasing a toxic substance that may endanger public health and the environment.

For wastewater management, the Environmental Protection Act (EPA) was passed in 1986. Under this act, EPA set the standards and emission limits depending upon the nature of the individual industry. In India, a Solid waste management rule was issued in 2016 for municipal solid waste and non-hazardous solid wastes. It is an updated rule of the Municipal Solid Wastes (Management and Handling) Rules, 2000 by the Government of India. In India, Hazardous and Other Wastes (Management and Transboundary Movement) Rules were amended in 2015. The new set of rules for construction and demolition wastes are called Construction and Demolition Waste Management Rules, issued in 2016. Unfortunately, both large- and small-scale industries rarely pay attention to the proper treatment and disposal of these industrial wastes. The new revamped Hazardous and Other WastesRules, 2016 enacted that authorities have to pay penalties violating rules for transportation, storage, and proper recycling of these hazardous industrial waste, including electroplating, metal processing, galvanizing, refinery, petrochemical, pharmaceutical, and pesticide industries. Currently, there are only 17 disposal facilities, including secured land-fills and scientific incinerators. Inferior waste management scenarios exist like other developing countries due to insufficient scientific recycling and disposal facilities. Furthermore, different wastes from industrial processes, municipal wastes, and other wastes seem even higher than reported. Regulations for waste management is supposed to be most onerous, whereas it seems to be most loosely regulated.

2.4. Environmental Impacts of Waste Management

Wastes in general (solid or liquid) can be hazardous or non-hazardous, yet both can be toxic. Hazardous waste is harmful to humans and the environment and is mainly discharged from industries like non-ferrous metal extraction like copper, zinc, lead. The non-hazardous inorganic solid waste includes municipal solid wastes, residues from coal combustion like coal fly ash, red mud from bauxite ore, tailings from primary processing of aluminium, iron, etc. Different types of hazardous and non-hazardous wastes from various sources with their generation value per capita in India are enlisted in Figure 5.

The enormous volume of wastes generated has a high impact on the environment. The International Solid Waste Association (ISWA) reports that uncontrolled dumpsites hold 40% of the world's waste. D-waste survey, 2014 states in different continents, a vast area of 2175 hectares belongs to 50 large open dumps that can directly affect 64 million lives which is eventually equivalent to the population of France (Law and Ross 2019). The dumpsites now hampered coastal and marine lives and can become a source of a disease outbreak. Uncontrolled land-fills and non-engineered open dumps release methane, which is 25 times more potent than carbon dioxide for accelerating climate change issues. Without any stern step, open dumps will contribute 10% of global greenhouse gas emissions by 2025 (Law and Ross 2019). The toxicity associated with these wastes has long-term defects in human health and the environment if not managed properly. The toxic substances common to municipal and industrial waste are Cadmium, Lead, Mercury, Arsenic, Phenol, VinylChloride, organic dyes, etc. Most heavy metals released from different sources are very carcinogenic (Maharana et al. 2021). These polluting elements can also cause severe harm to aquatic lives if released without any treatment into the open environment. The toxic effect and health hazards associated with some critical wastes are tabulated in Table 1.

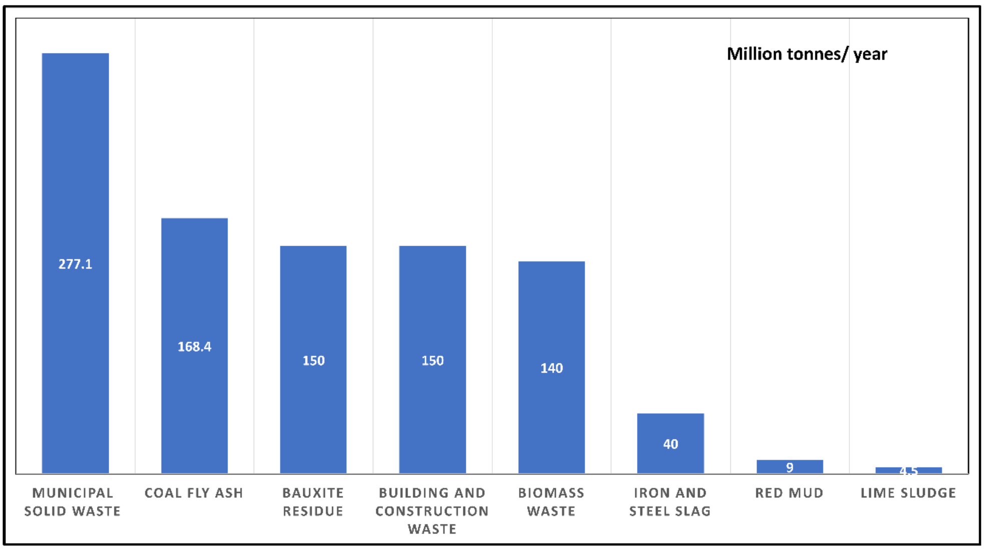

Figure 5. Current solid waste generation status in India in 2019-20.

Table 1. Toxic effect and health hazards associated with waste substances

Source of waste	**Pollutant**	**Toxic effect and health hazards**
Batteries, ink, paints, steel processing	Cadmium	Carcinogenic, kidney damage, renal disorder, soil contamination
Dyes, sealants, varnishes, steel processing	Lead	Brain damage, Defects in the circulatory and nervous system, soil contamination
Fluorescent lamps, batteries	Mercury	Dermatitis, kidney disease
Adhesives, coke oven wastewater	Phenol and its derivatives	Anorexia, liver effects
Silicon materials, mining	Silicon dust and residues	Chronic respiratory problems, irritation in skin and eyes
Electroplating, smelting	Zinc	Short-term illness, lethargy, depression
Electrorefining	Copper	Liver damage, headache, diarrhea, Willson's disease, long time exposure irritates nose, eyes, and mouth
Plastics, apparel	Vinyl Chloride	Carcinogenic, Mutagenic

A high concentration of toxic substances deteriorates the total environment, including humans, animals, and other living organisms. Though there are rules and regulations for maintaining the safe disposal of waste, unfortunately, they still exist on paper only. The current waste disposal system mainly deals with the end-of-pipe impacts of waste management. But the thing is to understand that the whole chain of activities from extraction raw materials to end products and its disposal leaves its footprint in the environment. A modern management system should rely on recycling or reutilizing the waste by recovering valuable resources present within it to reduce footprint.

Additionally, microplastic pollution is introduced recently as an extra burden to the green environment and public health. Microplastic is a polluter and a carrier of pathogens and antibiotics that can severely damage a healthy food chain. It can be easily introduced to the environment through (i) untreated wastewater, (ii) unscientific land-fills, (iii) run-off from waste heaps through rainwater (Vethaak and Leslie 2016; Das et al. 2019). Presently, approximately 5 trillion microplastics are loaded in the oceans and are expected to double by the end of 2025 (Gallo et al. 2018). Proper waste management in terms of recycling and waste disposal strategies has to be taken up to restrict environmental depletion.

3. Sustainability Planning Approaches

Sustainable planning approaches demand addressing the problem, design of planning, giving robust and acceptable solutions in a real complex system that may change with circumstances. Thus it requires a total understanding of technical, social, environmental issues that comprise economic solutions (Moallemi and Malekpour 2018; Fuldauer et al. 2019). Sustainable planning would be based on a circular economy approach compatible with an uncertain future against traditional linear optimization methods. The methods can be divided broadly into two approaches like quantitative and qualitative (Fuldauer et al. 2019). The quantitative approach involves the implication of scenario planning and evaluates the investment. The qualitative approach involves the generation of future scenarios aiming for a sustainable future. So what is a scenario? “Scenarios are consistent and coherent descriptions of alternative hypothetical futures that reflect different perspectives on past, present, and future developments, which can serve as a basis for action” by Van Notten (Van Notten 2005). Scenarios similar to approaches can also be explained qualitatively or quantitatively, or both. In simple words, long-term sustainable scenarios would be a qualitative narration of future progress for complex practice on the basis of quantitative formal modelling. Participatory planning approach allows integration of stakeholder views on factors which are influential to sustainable development and predicting scenario assumption on regional context.

3.1. Quantitative Planning Approach

Quantitative planning involves detailed modeling, investigate the impacts of different uncertainties. The Robust Decision Making (RDM) approach can play a significant role in determining infrastructure opportunities and, most importantly, decide which can be more robust in socioeconomic uncertainties (Fuldauer et al. 2019). This planning approach has been successful for infrastructure development in developed countries, but the situation is not so smooth for developing countries (Bhave et al. 2016). The two main constraints for the developing countries are: (a) inappropriate data collection and its regular update on which one can develop scenario modeling; (b) uncertainty of the future that fails to capture apposite complexities in the transition from linear to circular waste management approaches (Fuldauer et al. 2019). Qualitative participatory approaches can solve these limitations.

3.2. Qualitative, Participatory Approaches

Qualitative scenario planning approaches involve stakeholders for data collection, platform generation, and dictation of the path on which change can be beneficial. An alternative to traditional planning and forecasting was developed that is the backcasting method (Robinson 1982). Backcasting method has been specially planned for analyzing sustainable policies. Suitable application of interactive backcasting (Van de Kerkhof et al. 2002), as a participation tool, include (i) formulation of the problem and scope of the assessment, i.e., identification of sustainable development strategies for a specific region over a while (generally 20-50 years for backcasting), (ii) involvement of interested participants from the government, companies and NGO’s, (iii) involvement of scientists by oral presentation or writing to assist the participants for making better future. Sustainable development can combine different tools like backcasting, upstream thinking, ecological footprint, and LCA (Life Cycle Assessment) (Robèrt 2005). Many participatory methods face limitations in several stages, like selecting stakeholders and their engagement rate, time lag, and resource restrictions (Fuldauer et al. 2019). Therefore, for successful sustainable waste management, an integrated methodology involving a large majority of decision-makers of national infrastructure as well as stakeholders from different backgrounds is necessary.

4. Integrated Waste Management Methodologies: An Approach for Attaining SDG

The United Nations (UN) launched Sustainable Development Goals or SDGs in 2015 with 17 goals and 169 targets to be met by 2030 for all nations to boost economic growth, social inclusion, environmental protection (Stafford-Smith et al. 2017; UN 2015). Among 17 goals, this chapter is mainly concerned with two goals are goals six and goal 7. Goal 6 aims to ensure availability and sustainable management of water and sanitation for all, and goal 7 aims to ensure access to affordable, reliable, sustainable, and modern energy for all. The integrated waste management methodologies involve four interlinked steps (i) understand the current system: consist of pros and cons of the existing system, (ii) identify future needs: strategy development, policies implication, SDG targets, (iii) simulate, evaluate, and recommendation (Fuldauer et al. 2019). These methodologies will help upgrade existing waste assessment tools by expressing social, environmental, and economic pathways for better forecasting waste management and decision-making.

4.1. Understanding Current Challenges and Future Needs

This step involves data collection for mapping the current infrastructure of waste management sectors. Multi-level stakeholder mapping will allow us to understand sustainability performance. The modeling framework will be based on three essential tools: scenarios that can deal with the uncertainty of the future, strategy development with a vision of the future, and Key Performance Indicators (KPI) that evaluate the strategy (Fuldauer et al. 2019). Whereas translation from qualitative into quantitative requires the appropriate data compiled from the interviews of expertise, stakeholder, and national database. While doing so, prime data that we are concerned about may be lost, and then correct data should find out from other sources or databases. Transparent documenting and update the database will assist in modeling and future needs. For example, the main issues associated with solid waste management are waste generation, waste collection, transport, and disposal. There is a lack of data in each stage of the waste management cycle around the world. The current issues and future needs are briefly summarized in the following sub-sections.

4.1.1. Waste Generation

Waste generation volume seems to be proportional to the per capita income of a country, as we have already mentioned in the previous section. The developing countries like us waste generation trend have reached the critical state with a rapid population. Currently, India generates 62 million municipal waste per year. Among which 43 million tonnes (MT) of waste is collected, 11.9 MT is treated, and 31 MT is dumped in land-fill sites. The scenario is getting worse in poor and marginal countries. There is a lack of awareness among the people resulting in inappropriate garbage handling. Under this circumstance, to reduce the waste burden, future demands are to educate the citizen and install a recycling system in the house (Loan et al. 2019).

4.1.2. Waste Collection and Its Transport

The process of waste collection or segregation is the main difficulty in many countries. Open dumping on the roadside and public places are standard practice in cities. Street sweeping for the collection of waste is an everyday practice that is mainly done by unskilled rag-pickers. This street-sweeping frequency is also proportional to the income level of a country. For example, the sweeping frequency was once a day in Tokyo, Japan, whereas, in Guwahati, India, it was twice a week (Gogoi 2013; Das et al. 2019). There should be proper waste segregation based on categories like biodegradable, non-biodegradable, glass, and combustibles for a sustainable waste management scenario. Since the service of municipal authorities in urban areas is to provide different bins for collecting the waste, but it rarely follows the proper method. It is mainly due to the unawareness of citizens and service workers that waste segregation plays a vital role in the recycling process of waste.

Additionally, the longer the residence time of waste in public areas will germinate health and environmental hazards. Therefore, it is urgent to educate people via social campaigning to spread awareness of waste collection and its segregation from its source. In India, waste pickers play a significant role in the waste collection since it is the primary source of income in many families. A recent study published that the waste pickers in Pune, India collect organic waste for composting and biogas generation (Kumar et al., 2017). They also mentioned that study for waste collection in six cities in India waste pickers team of 80000 people recovered about 20% of waste, and they reduced the emission of 721 kg of CO_2 per annum. Waste collection and its transport share are more than three-fourths of India's solid waste management budget. Like developed countries, we don't have an automated system for waste collection. The skilled labor for this process is necessary, and 30% of the total costs of waste treatment will be utilized for staff wages and service maintenance (GGGI and TERI 2015). It is worth mentioning that one of the cleanest villages of Asia is Mawlynnong (Meghalaya), India (Das et al. 2019). The villagers use bamboo bins to collect waste and compost the pit. Then the compost was used for gardening and in-house vegetation. The villagers get training to keep the cleanliness of the village and imposed fines on the violator. This is the live example of public awareness of sustainable waste management and recycling, and the future needs more such effort, initiatives, and implications for attaining SDGs.

4.1.3. Waste Treatment

The operational efficiency depends upon the design of the process, run time, efficacy, and economic feasibility. The existing waste treatment method is not very economically sound as it consumes 2-3% of the energy consumption in a developing country (J. Xu et al. 2017). Thus, the future of waste treatment requires a transformation from mechanical operation to biological process. For example, wastewater treatment using membrane bioreactors are posing great potential to reduce energy costs. The developed countries like the US, Japan, South Korea have a large number of incineration facilities for waste treatment. But for highly populated developing countries with very small proportions of arable lands, the 4R (Reduce, Recycle, Reuse, Recovery) technology for waste treatment can be a sustainable pathway. The ultimate fate of waste after recovery of resources will be into the environment via land-filling or direct release with only motivation is to take that there should be a reduction of carbon footprint. The advancement of waste treatment methodology aims to reduce the footprint by recovering resources at their highest efficacy.

4.2. Strategy Development

Strategy development is a crucial step after understanding the current scenario and analytical mapping. The next step is to involve influential personalities to promote a sustainable waste management vision by 2050. Back-casting will help to design a strategy for an uncertain future. Investment should make for five different categories legal, economic, infrastructure, land use, and information. Unlike other participatory approaches here, the consensus is not the motive. But to make group investment from different constructing visions to build more robust and sustainable infrastructure. Thus, it will allow diversifying the strategic models for achieving the vision since it is not any individual stakeholder's thought but a combination of multiple views capable of implementing their strategies in practice (Fuldauer et al. 2019). This strategy development can also be helpful for assessing infrastructure performance of methodologies that focus on realistic alternative investment rather than optimal strategy. The methodologies have been developed to determine infrastructure performance on three grounds: service provision, carbon, and cost (Otto et al. 2014). The Key Performance Indicators (KPI) can easily be linked with SDGs in environmental, social, and economic sectors. The SDG targets and indicator applicable to waste sector of small island developing states (SIDS) has been systemically reviewed by (Fuldauer et al. 2019). They mentioned that national employment is one of the important performance indicators for strategic infrastructure planning of sustainable goals.

4.3. Simulate, Evaluate, and Policy Implication

The last stage of the integrated waste management framework is to simulate the quantitative models of back-casted strategies of stakeholders based on indicators of sustainable development goals. Then evaluate the data on different socioeconomic, environmental situations like democratic changes, economic growth variation, fuel price fluctuations. The modeling applicable for the waste sector for sustainable infrastructure planning was already published in detail elsewhere (Hall et al. 2016; Fuldauer et al. 2019). A sustainable infrastructure framework requires multiple-level research coordination and updated information discussion with the government, institutions, organizations, and the common population to upgrade the data in an iterative loop. This action will remove some mental barriers to implement policies and add positive behavioral change effectively. The main target is to involve entrepreneurs, consumers, funding bodies, investors, and governments promoting new opportunities for novel sustainable business in integrated waste management.

5. Cost-Effective Waste Utilization Technologies: Waste-to-Energy/Resource Recovery

There has been a considerable change in sustainable waste management methodologies over the last 40 years. This chapter mainly focuses on effective waste utilization technologies for solid waste (to be more specific municipal solid waste) and wastewater (released from different industries). The top-down tiered approach by US-EPA for solid waste management was widely accepted hierarchy practice previously. The integrated waste management practices are as follows: reduction at the top (least preferred), followed by recycling, composting, combustion, and land-filling at the bottom that represents a more preferred practice. With an exponential increase in population and industrialization in the 21st century, the familiar pyramid of waste management practices is expected to be inverted in upcoming years where waste disposal or land-filling are least preferred; source reduction and reuse is the most preferred method (Figure 6). Since it is a relatively new concept to adopt, differences exist in opinions. Many think that the inverted pyramid may not be self-sufficient to justify the positive result of waste conversion technology from the perspective of life-cycle and economic assessment of waste. Many parameters affect life-cycle assessment like energy balance between energy consumption and energy generation or toxic gas/water release to environment or disposal requirements for residuals. The footsteps for future sustainable waste management would rely upon (1)Dismissal of land-fill disposal and enhancing recycling objectives, (2) Independence of energy on local, regional, and national grounds by boosting the production of green energy, (3) Acquaintance of sustainability and climate change initiative, (4) Alternative water supply requirement, (5) Local financial development and high-value jobs. There is an urgent need for suitable waste conversion technologies to produce green energy, used internally or for other systems. Integrating multiple disciplines such as solid waste management, recycling, wastewater treatment, reclamation of waste is imperative to attain sustainability. It is noteworthy to mention that each domain has become more specific and effective in solving its issues. Still, the benefits of taking advantage of synergies between different systems are not realized yet. For example, an integrated system of solid waste management can treat wastewater by producing electricity. Likewise, many processes can be integrated to manage waste for recycling, conversion, recovery, and ultimately disposal. Therefore, integrated waste-to-energy conversion methodologies will introduce a robust and flexible system to sustain seasonal market variations.

The emerging waste conversion technologies for solid waste are - incineration or mass burning, refused derived fuel combustion (RDF) for production of steam and electricity, land-fill gas to energy (LFGTE) for the generation of electricity, thermal and plasma gasification/vitrification, anaerobic digestion or co-digestion for production of methane, catalytic depolymerization for production of liquid fuels. The mentioned emerging technologies are mainly at the preliminary stages of the process not commercialized yet. Nevertheless, they became viable options over time and can be quickly adopted in the near future. Thus, the later section deals with promising opportunities for the above technologies for solid waste and wastewater management.

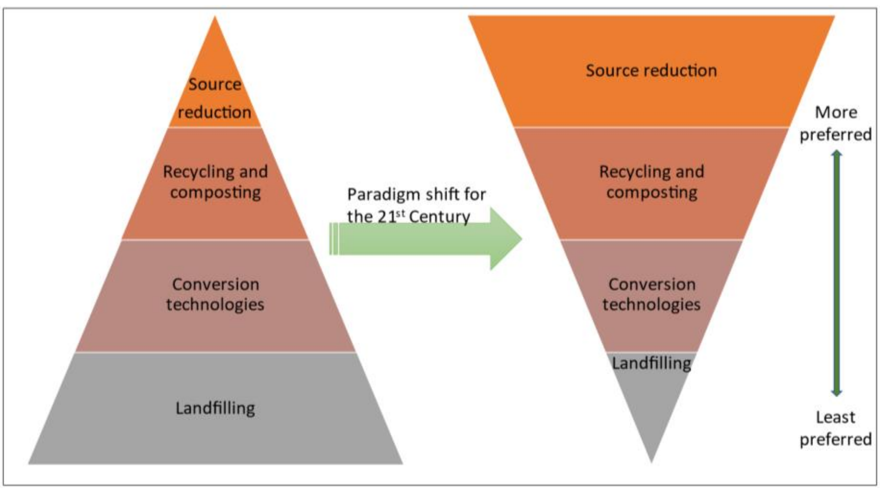

Figure 6. Evolution of solid waste management for the 21st century.

5.1. Thermochemical Conversion Technologies

Conversion pathways for waste to energy can be divided into three distinct methodologies: thermochemical, physicochemical, and biochemical, for treating municipal solid waste, as shown in Figure 7.

Thermochemical conversion technologies include combustion, gasification, pyrolysis, refused derived fuel. Combustion technology is relatively old compare to other thermochemical treatment processes. Gasification and pyrolysis are now emerging technologies that can be easily incorporated into a sustainable waste management system.

Gasification is usually done under high temperatures in the presence of oxygen and/or steam, and pyrolysis occurs under low temperatures in the absence of oxygen. The ultimate product of pyrolysis and gasification is synthesis gas (H_2 + CO) via partial oxidation of organic matter present in the waste. Heating value varies between 200-500 BTU/cubic feet, which is half or less than that for natural gas. But it has significant advantages as it can be used for multiple purposes like generating heat and power, as quality gas in pipelines, or producing many liquid fuels. Researchers find that gasification technology has a high potential to be commercialized in the next few years. Syngas is considered a replacement for natural gas that can be used in many industrial processes. In gas turbines, syngas can be used as fuel for electricity, combustion, or steam generation.

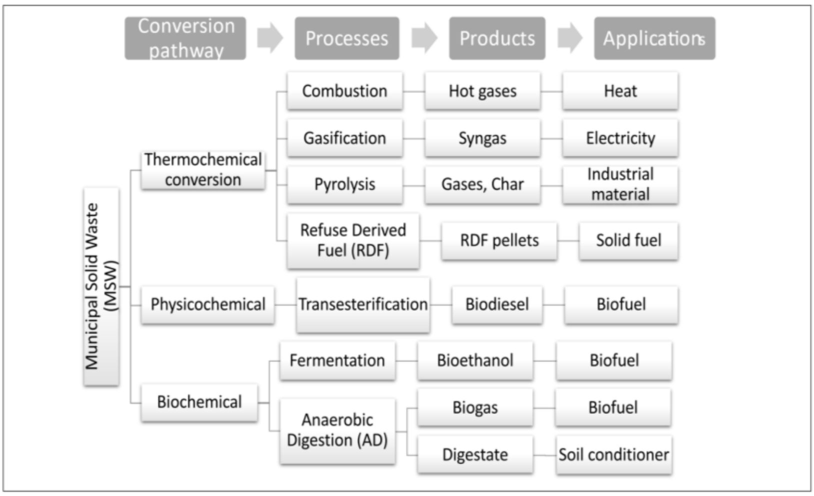

Figure 7. Waste-to-energy conversion pathway of municipal solid waste (MSW).

Thermal plasma gasification technology has received significant attention in recent days over other technologies since it has (i) high energy density and temperature, which offers fast reaction times with large throughput in a small furnace, (ii) high heat flux density allows rapid start-up and shutdown times which is a bit difficult in incineration, and (iii) minimal amount of oxidant is necessary to produce syngas. The detailed study on thermal plasma gasification of municipal solid waste with a case study of a commercial-scale pilot plant demonstrates that it is an entirely economically feasible and mature method that ought to adopt in a sustainable waste management system (Byun et al. 2012). It produces not only syngas but also other utilities and liquified petroleum gas (LPG) with minimal air pollutant emission compared to the conventional incineration method. The vitrified slag can be used as a construction material. By this technology, the main target of reducing land-fills will undoubtedly be attained and additionally utilized perfect valorization of solid waste (Ramos, Teixeira, and Rouboa 2019). Therefore, in a nutshell, thermal gasification is a truly sustainable waste to energy technologies in terms of lower environmental impacts with a higher yield of renewable energy.

Another emerging waste-to-energy technology for solid waste management is Refused Derived Fuel, commonly known as RDF. RDF is a fuel that is easily combustible in conventional combustion boilers produced from municipal solid waste after sorting from non-combustible solid material like glass, stone, metal. After sorting from non-combustible portions, RDF gets pelletized and sold as fuel which can be mixed with coal or with biomass waste in power plants. Developing countries like India are deliberately looking for an alternative to fossil fuel for our energy independence. RDF is the best green fuel for us since it reduces municipal waste load and fulfills energy requirements. We have already discussed that municipal solid generation is proportional to population.

Similarly, the generation of electricity from RDF plant will be sufficient to meet the need of the high population. India has quite a few RDF plants in Lucknow, Hyderabad, Tamil Nadu, Rajkot, Mumbai (Ganesh et al. 2013). Electricity from RDF, waste to energy technology, is widespread common practice for handling municipal solid waste worldwide and is expected to grow higher in the near future.

5.2. Physicochemical Conversion Technologies

Sustainability relies on finding renewable alternatives to conventional fossil fuels. According to the World Bioenergy Association statistic report, it is estimated that renewable energy sources can fulfill about 13-14% of total energy consumption. Waste cooking oil is found to be a very popular and efficient raw material for biofuel production by transesterification process, an example of waste conversion to renewable fuel. Parametric sensitivity study was conducted on waste cooking oil by varying different parameters such as operating temperature, the molar ratio of alcohol to oil, types of catalyst and its concentration, reaction time, moisture, and free fatty acid content (Banerjee and Chakraborty 2009; Nurfitri et al. 2013; Leung, Wu, and Leung 2010). Supercritical transesterification eliminates the pre-treatment cost of lab-scale biodiesel production from waste cooking oil (Van Kasteren and Nisworo 2007).

5.3. Biochemical Conversion Technologies

Biochemical conversion of waste involves mainly two methodologies fermentation and anaerobic digestion (Figure 7). Both the process is often used to treat organic matter present in municipal solid waste and wastewater streams. These processes can reduce emissions of greenhouse gases, leaching nutrients and organic matter into the environment, pathogen levels, weed seeds, and odor. Anaerobic digestion (AD) occurs naturally in soil and lake in the presence of bacteria which converts organic waste into a mixture of gases (consist of main methane). This methane can be used to generate heat and electricity. In the land-fill sites where wastes are buried, methane generates naturally by anaerobic digestion and escapes. But now, several projects and development by government and local bodies are going on to capture land-fill gas to produce renewable energy around the world. Though lignocellulose substrate can produce biomethane by AD efficiently, the efficiency of biomass conversion gets reduced by the presence of recalcitrant cell wall and complex chemical composition of the substrate (N. Xu et al. 2019). The new research trend focuses on enhancing bioenergy production from waste and reducing the waste load in land fillings. Anaerobic co-digestion is a promising technology for increasing methane production and materials recovery from waste sludge. Wastewater mixed with food waste and cheese whey enhances methane production by

31% for the reactor dealing only with activated sludge (Hallaji, Kuroshkarim, and Moussavi 2019). A Higher C/N ratio enhances the co-digestion of waste sludge, thereby increasing methane production and simultaneously increasing organic matter removal. Numerous publications are based on the ADM1 model that can optimize the anaerobic co-digestion method's limiting factors (disintegration and hydrolysis). The biochemical methane potential (BMP) is a very compatible tool for determining the biodegradability and decomposition rate of organic materials (Hagos et al. 2017). The two-stage AD consists of the hydrolysis-acidogenesis step followed by methanogenesis. It has several advantages over single-stage: (i)increase stability and pH is controlled, (ii) higher loading rate, (iii) higher methane yield, (iv) higher reduction of COD and volatile solids (Hagos et al. 2017). The two-stage bioreactor is more efficient in producing more biogas and biomethane over 100% (Rabii et al. 2019). Apart from conventional organic waste like agricultural, food, and municipal the sludge generated from wastewater treatment plants or boiler manure or steel making slag can also be fit into anaerobic digestion and co-digestion process for generating a significant amount of renewable resources and fertilizers (Truong et al. 2020; Sarikaya and Demirer 2013). Many researchers claim that there are even higher revenues for the production of biofuels from waste than the production of bioelectricity. Besides, there are specific barriers too for commercializing renewable fuels in terms of favorable economic terms and conditions. Liquid or gaseous biofuel is strictly regulated by certain specifications. The cost of the production of biofuels from waste is not yet fixed. Thus, the whole system must clarify these hurdles and improve relations with private financing bodies for long-term projects.

5.4. Resource Recovery from Wastewater

Wastewater is no longer considered as waste but as a sustainable resource for energy and other value-added products. It contains 80% thermal energy and 20% chemical energy that can be recovered if treated sustainably. European nations are the global leader for the "waste-to-energy" movement. The emerging technology combines with conventional anaerobic digestion to produce methane which is simultaneously being used to produce electricity for supply onsite power facility. This is called combined heat and power (CHP) or cogeneration system that fulfills both requirements using a single source (U.S.EPA 2014). The Marselisborg wastewater treatment plant in Aarhus, Denmark, has produced 30% more electricity and 80% more heat than consumed, resulting in over 150% net energy recovery from waste (State of Green 2021). The question normally arises when we have a better option to produce direct electricity in a microbial fuel cell (MFC) by treating wastewater; what the necessity of producing gas energy in microbial electrolysis cell (MEC) to generate power is? The answer relies on studying life cycle assessment among three energy-producing technologies MFC, MEC, and AD. It states that MEC has higher economic and environmental benefits over MFC and AD (Foley et al. 2010). Though membrane-less MEC reduces the capital cost, other factors like pH and methanogens limit pure hydrogen production. Thus, researchers are now moving towards the production of (bio)hythane (a mixture of methane and hydrogen) from wastewater and its utilization in current natural gas-operated engines (Huang et al. 2017).

Nutrient (nitrogen and phosphorus) recovery from wastewater is an important sustainable reclamation route for wastewater treatment. It is based on the "partition-release-recovery" mechanism where biological agents are used for recovering nutrients from waste (Puyol et al. 2017). Recovery of nitrogen and phosphorus from the waste stream is ultimately utilized for the production of fertilizers. The conventional route for synthesizing fertilizer via ammonia is an energy-intensive process. For Nitrogen recovery, several kinds of research are going on through stripping, precipitation, ion exchange, hydrophobic membrane, vacuum membrane (Van der Hoek et al. 2018). It is not yet competitive with agricultural demands. But N-recovery can be cost-effective if we managed to reduce electricity and chemical consumption during the process (Shaddel et al. 2019). For Phosphorus recovery, it is mainly done by concentrating it in sludge. Struvite precipitation is most advantageous for treating wastewater in combination with AD. Phosphorus recovery is much easier than nitrogen recovery from waste because of its low investment and operational cost, high recovery rate, and easy adaptability in the existing system (Shaddel et al. 2019). EU has no. of full-scale P-recovery plant followed by North America and Japan. The rest of the world still severely lacks it. The reason may be the low price of fertilizer from phosphate rocks. Several self-sustain wastewater treatment plant projects are ongoing to produce composite byproducts from waste sludge-like polyhydroxyalkanoates (PHA) and its composite, long-chain polysaccharides, fiber which have high commercial value (Puyol et al. 2017). The resource recovery from wastewater in India is now only at an infant stage. Unless and until it gives additional benefits or direct marketable products, recovery and recycling of indigenous resources cannot be economically feasible even though it fulfills environmental sustainability.

6. WASTE MANAGEMENT IN A CIRCULAR ECONOMY

The sustainable development agenda 2030 put sustainability at the forefront of global development. The rising stress on limited resources forces the governing bodies to adopt certain models, approaches, and system frameworks leading to sustainable development. A sustainable waste management system *minimizes the depletion of the resource base, protects and promotes human health, minimizes environmental degradation, is technically and institutionally appropriate, socially acceptable, and economically viable in the long term* (Sustainable Sanitation Alliance (SuSanA) 2008). The circular economy approach is one of the emerging paradigms that should be adopted to shift the linear value chain into less carbon and less polluting economy. A comprehensive definition for understanding the circular economy concept for waste management can be framed as an economic model aiming for efficient usage of resources through waste minimization, long-term value retention, reduction of primary resources, and close loop products within the boundary of environmental and socioeconomic benefits (Priyadarshini and Abhilash 2020). The four major tools for sustainable management are waste prevention, reuse, recycling, and recovery. The successful implementation of these tools is the baseline of a circular economy. Waste prevention is at the top of the waste hierarchy. Waste prevention at its source is only the way to reduce waste generation load. For that, the segregation of waste is a compulsory task. For example, separating organic materials from municipal waste and food waste is a must-do job to convert it into a highly economically valued product like methane, hydrogen or other gases, bioethanol or biodiesel, and other composite materials. Many countries adopt policy measures aiming to reduce waste consequently leads to overall decrease in raw materials and emissions created by linear value chain. Recycling the waste reduce cost of raw materials and reuse reduce waste handling load. One of the central pillars of waste circular economy is to feed the waste into the economy by recovering its revenue value from resources avoiding waste disposal in land-fill or other as far as possible. In European countries, the circular economy concept has gained immense priority in policymaking as a positive and solution-based perspective for economic development. China has formulated the Circular Economy Promotion Law (2009) and the Circular Economy Development Strategy and Immediate Plan of Action (2013) for economic development within rising environmental restrictions (Priyadarshini and Abhilash 2020). In India, the integration of circular economy in major areas like waste management and renewable energy influencing economic development within a policy framework is highly lagging behind time all over the country. Policymakers should understand the potential impacts of waste management activities in value recovery mechanisms for the long run rather than realizing the only short-term impact of the end-of-pipe solution. There is a wide disparity between waste generated and recycle in all types of waste. To be specific, India recycled only 23% of solid municipal waste as of 2017. Resource recovery and renewable energy recovery through waste material recycling will not only improve the foster growth of the circular economy in India but also reduce reliance on other countries for imports. The sustainable waste-to-energy conversion technologies will have added advantages of a circular economy and achieve total sustainability of a country through providing employment, reducing environmental footprint, and greenhouse gas emission. Therefore, proper segregation and selection of appropriate waste conversion technologies is the most important thing. The process optimization should be done for upscaling pilot-plant projects and demonstrative projects to implement the integration of waste management with a circular economy. A wise investment and appropriate technology can knock-off serious challenge and also generate capital for waste management. Similar realization exists for wastewater treatment too. Wastewater is now considered as resource of nutrient and energy and treated water can be reused to fulfill utility requirement. Apart from technical aspect, public participation has to be integral part of the development and decision-making framework. Only implementation of rules and regulations won’t help its success. Recycling and reuse have to be centralized in circular economy approach by improving waste management practices.

7. The Way Forward

A sustainable planning approach is nothing but incorporating three “E” s – economy, environment, and equity-into the strategy for developing a new management system or upgrading the existing ones. A waste audit is the first crucial step in the reduction of waste volume. Only then we can identify opportunities for waste reduction, recycling, resource recovery. After fixing the initial target of what amount of waste is to be treated, we can target how much can be recycled or recovered from waste. The next step involves documentation of total cost analysis of the waste life cycle. Waste-to-energy is now a relatively hot topic in terms of sustainability and attaining SDGs. Waste is now considered a potential energy source, for example, capturing land-fill methane to generate electricity or fuel and converting organic waste into green renewable fuel. Total cost accounting identifies the cost associated with waste handling to energy or resource-producing technologies and, ultimately, the revenue cost of the product. It will help local and global policymakers to implement new waste conversion technologies in a sustainable planning approach. Community involvement is one of the major restrictions in terms of pricing, technological, safety, and regulatory changes. The transition from linear to circular economy approach will synergies many factors such as integration of solid waste management in wastewater treatment improves job opportunities (9 to 25 million worldwide) with a lesser risk of health hazards, more efficient use of water, and reuse of waste material by implementing robust incentive. What we need to understand and address market regulatory conditions to promote sustainable waste management. The global waste management market was USD 2080 billion in 2019 and is expected to reach USD 2339.8 billion in 2027, at a CAGR of 5.5%. The market's growth globally reflects proactive government measures to avoid illegal dumping and reduce the waste load in the environment. The existing approach will hamper the market growth.

Conversely, awareness of people and government bodies will help promote waste-to-energy solutions, which eventually smoothens the growth opportunities of market players. Regardless of sustainable planning and approaches, updating existing setup or technologies for remediation is only the first step in a much larger process. The success solely relies upon the adaption and engagement of the whole community like governments, residents, businesses, and civic organizations. In brief, emergent actions can be summarised as follows (1) International aid and funding should be mobilized for the betterment of waste management conditions in developing countries, (2) A participatory approach should be taken for integration between solid waste management and wastewater treatment, (3) Boost up an existing recycling system and promote resource recovery revenue from waste, (4) Producer has to be more responsible for waste management rules and amendment and its safe disposal.

CONCLUSION

Sustainable waste management will play a significant role in attaining SDGs by 2030 worldwide. This chapter thus represents a current global waste management scenario, including waste generation, waste treatment, regulation, and environmental impacts. The qualitative sustainable planning approach aims to generate future scenarios, while the quantitative approach involves the implication of scenario planning and evaluation of the investment. For successful sustainable waste management, an integrated methodology involving a large majority of decision-makers of national infrastructure as well as stakeholders from different backgrounds is necessary. The integrated waste management methodologies involve four interlinked steps (i) understand the current system: consist of pros and cons of the existing system, (ii) identify future needs: strategy development, policies implication, SDG targets, (iii) simulate, evaluate, and recommendation. Apart from planning approaches and strategy development, this chapter also deals with emerging waste conversion technologies into energy and resources. Resource recovery and renewable energy recovery through waste material recycling will improve the foster growth of the circular economy of the country. Community involvement is one of the major restrictions in terms of pricing, technological, safety, and regulatory changes for a transition from linear to a circular economy approach.

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Chapter 2

CLASSIFICATION AND MANAGEMENT OF WASTE: UPCYCLING OF WASTE INTO NANOMATERIALS FOR WATER REMEDIATION

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ABSTRACT

Waste management is serious issue and without classification of waste it is very difficult to manage waste properly. This book chapter provides an overview regarding the classification of waste, importance of waste management, waste management approaches, new insights for upcycling waste to nanomaterials, significance of nanomaterials for water remediation and also the present and future challenges associated with waste management.

The up conversion of waste to value added materials i.e., activated carbon, Biochar, nanomaterials for water remediation have been done via carbonization, hydro-solvothermal treatment, pyrolysis etc. Nanoscience and nanotechnology have seen great progress in the last decade working in environmental remediation through environment friendly and economically appropriate approaches. The amazing physicochemical properties of nanomaterials make them an encouraging candidate for wastewater treatment. Nanoparticles have great adsorption capacity and are able to purify very low concentrations of pollutants in water with high selectivity. Adsorption approach to water remediation is simple and economically successful. So in this book chapter, we have studied mainly the adsorbents/nanomaterials which are synthesized by using waste as a precursor and show their efficacy for water treatment. Furthermore, this work is focused

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on the present and future challenges associated with the application of these materials in industrial scale.

1. Introduction

Waste is unusable or unwanted material which is considered as garbage and needs to be eliminated also its management is very important. The different sources of waste are industrial, agricultural, biomedical, municipal waste etc. According to “What a Waste 2.0" report published by the world bank in 2017, only the municipal waste source generates a huge amount of waste per annum, the report says that world generates approx 2.01 billion tonnes of municipal solid waste per year out of which a small fraction is collected and segregated. Global waste production is projected to increase 70% by 2050 and expected to reach 3.4 billion tons by 2050. (Starodubova, et al., 2021).

Worldwide, the average waste generated by per person annually is approx 270 kilogram and the range can vary from 40 kilogram to 1657 kilogram depending on the lifestyle of the person. The issue of waste management must be taken seriously otherwise in upcoming years situation will be worst. The term “Waste management” does not define only the cleaning of surroundings, but it also include all of the processes and activities that involve handling waste materials to maintain the cleanliness and keeping the good health of the people. The management of waste requires the logical planning to educate or aware people about the harmful effect of dumping or burning the waste in open because approx one third of municipal waste is openly dumped or burned by the people which causes the adverse effect like global warming, emission of toxic gases etc. So to find new efficient, cost effective way of waste management is necessary. Now the waste is recycled or upcycled using different techniques. Recycling is the process in which the waste was treated of reform into the object which can be reused by the people. This recycling plays a great role somehow for maintaining the amount of waste by using them but it’s not cost effective. On the other hand upcycling of waste leads to the production of high value added products like fuel, nanomaterials etc but these methods are very sophisticated and needs the purity concern.(Tewari et al., 2019, Tewari et al., 2021, Pandey et al., 2019).

2. Classification of Waste

Classification of waste is very essential for waste management and classifying them in a careful and robust way gives the stringent controls required for treatment, storage, and disposal of waste, in addition, it may lower the cost of waste management. Basically waste is classified into five main classes.

2.1. Municipal Waste

Well-organized management of waste is a grave issue for local self-governing organization like municipalities and municipal waste has turn out to be the main concern.

Basically, the waste collected from different regions like market, schools, houses, park, offices etc by the municipality is known as municipal waste. This class of waste consist everyday objects like food waste, plastic waste, paper waste etc, which needs to be disposed after the use. This disposed solid waste needs proper management. Solid waste management is intricate and pricey, and also very important as it is directly concerned with the health, environment and quality of life of the local people. The transportation and segregation of municipal waste is very essential, and even 70-80% of total municipal waste management cost is spend in these two components. Improper waste collection and disposal can lead to a serious risk of local disease outbreaks, water source pollution, and greenhouse gases. The compositions of municipal solid waste are represented below in Figure 1 as reported by Abdel-Shafy. (Abdel-Shafy et al., 2018).

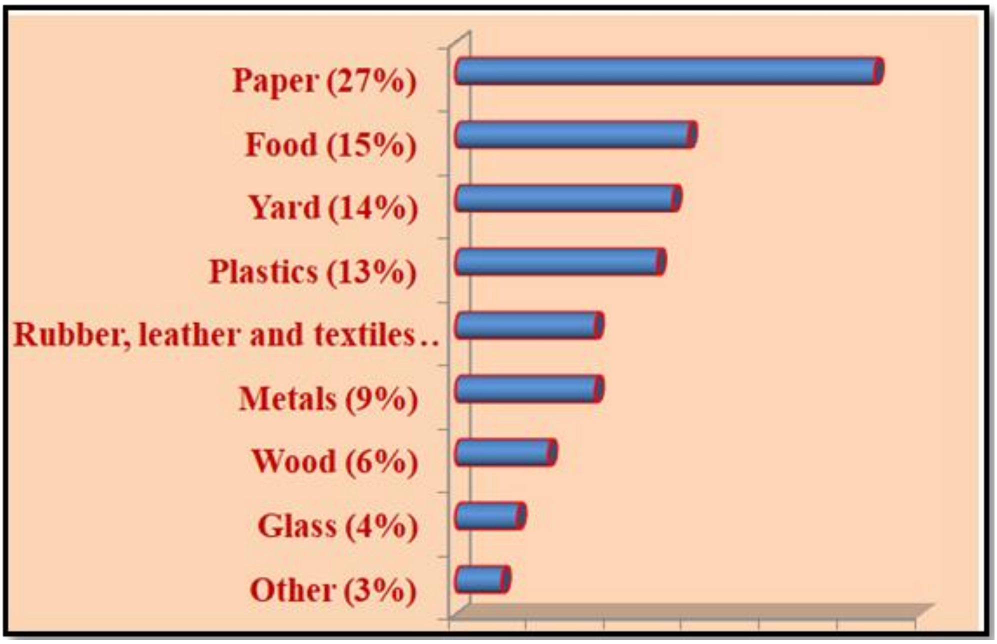

Figure 1. Composition of solid waste (Abdel-Shafy et al., 2018).

2.1.1. Household Waste

In the 21st century world is struggling with municipal waste management issue in which proper segregation of household waste plays a key role for its management (Stelmach, A. 2021). Segregation and recycling of household waste have been placed at a high priority in the waste management hierarchy as its management remains a major challenge due to its reliance on social behavior. (Jiang, P., et al., 2021) Household waste is the waste collected by municipality from the houses and it includes variety of waste like paper, plastic, glass, sanitary, garden, food, rubber, metal etc. This wide variety of waste needs to be segregated in the house weekly, quarterly as shown in Figure 2 (Stelmach, A. et al., 2021).

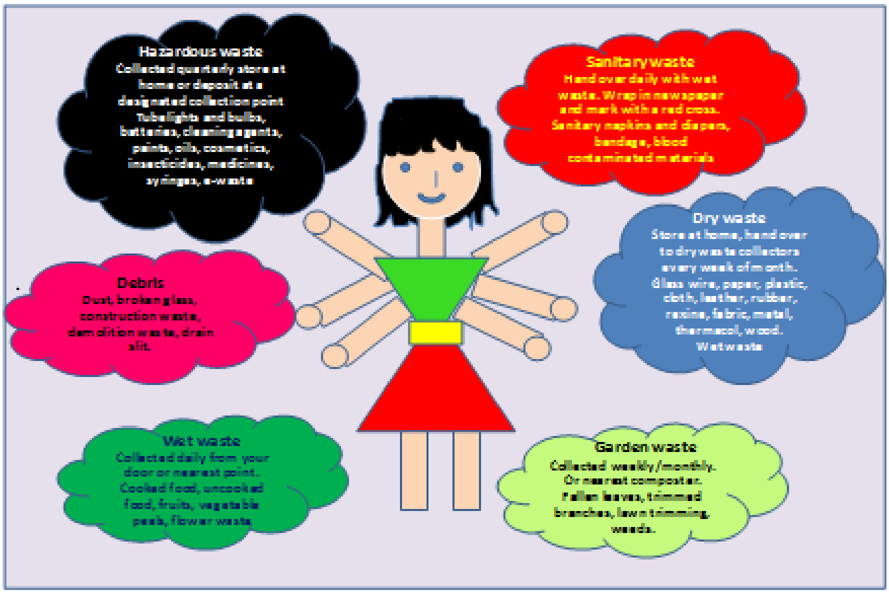

Figure 2. Different types of household waste segregate in house daily, weekly and quarterly.

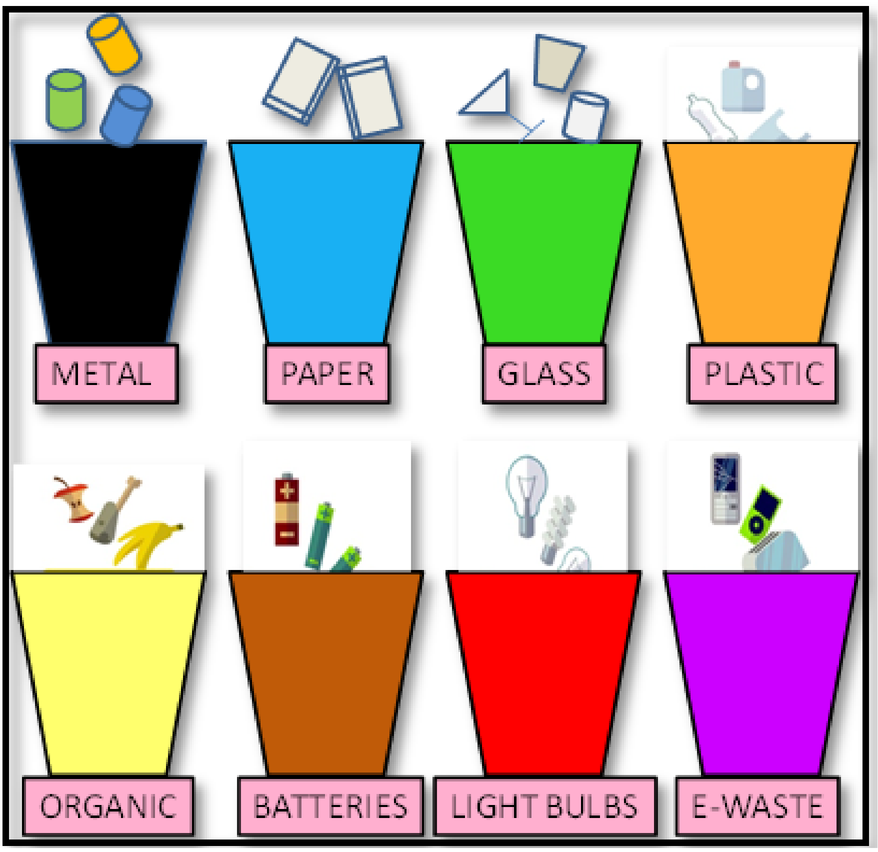

Figure 3. Different color of waste bins for segregation of different waste.

There are different colour of waste bins which help in segregation of waste. The Figure 3 shows different types of waste bins for different waste.

2.1.2. Commercial Waste

The commercial waste is the waste which is collected from the shops, banks, and public administration offices etc. Its composition is similar as household waste but its proportions may vary depending on the collection site. Various inorganic contaminants (e.g., Hg, Pb, Sb, Cd) are commonly present in commercial waste because these elements are formerly been used in the industrial production of numerous consumer goods. The composition of commercial waste is represented in Figure 4 (Viczek, S. A., et al., 2021).

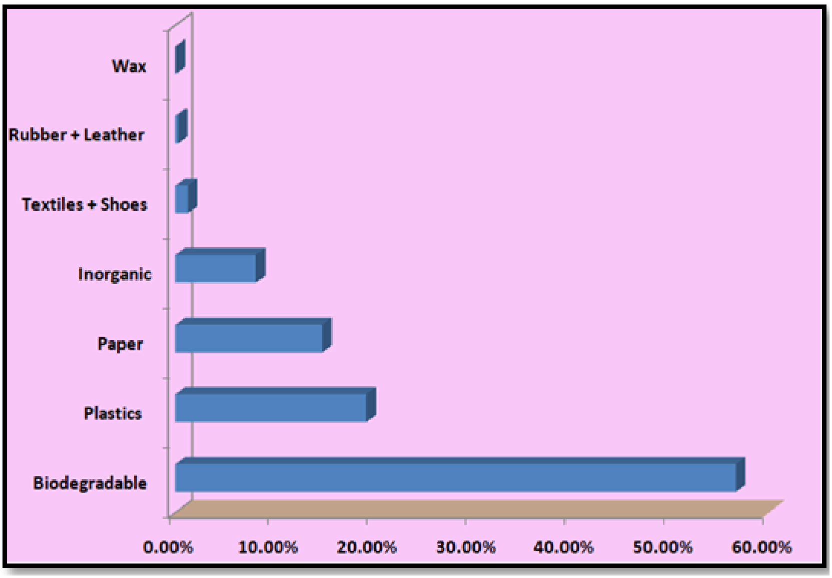

Figure 4. Commercial waste composition (%).

2.1.3. Demolition Waste

In this modern world, urban sprawl and inhabitants growth have resulted in anthropogenic activities like demolition of the old buildings, renewal of old or damaged building structures, construction of the new structures (bridge, road), mining, etc which leads to a significant increase in the amount of generated construction and demolition waste worldwide. The construction industry has become a huge industry and creates a lot of waste that has injurious impacts on the environment and natural resources (Yazdani, M., et al., 2021). Demolition waste is waste debris from destruction of buildings, roads, bridges, or other structures. The composition of debris varies but mainly it contain concrete, wood products, asphalt shingles, brick and clay tile, steel, and drywall. In India the composition of demolition waste is observed that 26% of waste is gravel type soil and sand, 32% is broken masonry, 28% of waste constituent by concrete and other 6% is metal, 3% is wood, and remaining 5% is other. The composition of demolition waste in India is represented in Figure 5 ((Pal et al., 2021).

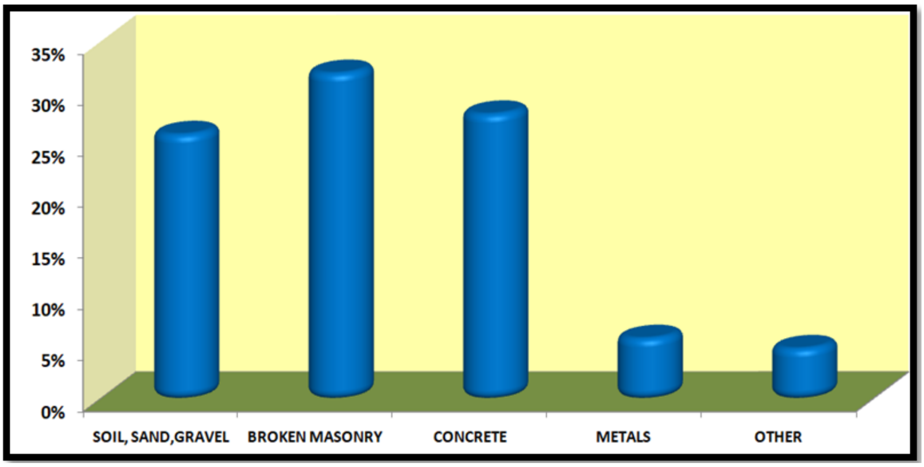

Figure 5. Composition (%) of demolition waste in India.

2.2. Agricultural Waste

Agricultural waste is defined as waste produced as a result of agricultural activities (wastes from farms, poultry houses, and slaughterhouses; veterinary medicines, or horticultural plastics, etc.). The uncontrolled decomposition of waste from agroindustrial sources can result in large-scale contamination of land, air and mainly water as water has been used for almost every treatment process including conversion and upcycling of waste. So researchers focus to minimize the contamination of water by proper waste disposal and treatment and for this they find new route to utilize the cellulosic agricultural waste materials as an abundant source for development of significant metal biosorption. The biomass enriched with various functional groups viz. amino, acetamido, carbonyl, alcoholic, phenolic, sulphydryl groups etc. act as significant adsorbent for various pollutants present in water and shows its great affinity towards the pollutants by formation of metal complexes or chelates through the mechanism of complexation, chemisorption, adsorption, diffusion through pores and ion exchange etc. (Sud et al., 2008).

2.3. Biomedical Waste

Biomedical waste is the waste which generates in field of biomedical, mainly for the diagnosis and treatment of the disease. The main composition of this wastes includes blades, bandages, discarded medicine, hypodermic needles, surgical cottons, gloves, clothes, and body fluids, human tissues and organs, chemicals etc., Other wastes generated in healthcare sector include mercury containing instruments, radioactive wastes, PVC plastics etc. According to World Health Organization 85% of hospital wastes are actually non-hazardous, 5% are non infectious but hazardous, whereas 10% are infectious (Remy, 2001). These wastes are now a danger to the public, as health care foundations are located in the heart of the city and therefore medical waste, if not managed properly, can be a potential hazard to the public and the surrounding environment. The segregation and collection of this waste is necessary and for this different color code have been fixed for disposal of different waste and also their treatment methods as listed below:

Table 1. Categorization of biomedical waste with treatment and disposal option

Category	**Biomedical Waste**	**Type Of Bag/ Container To Be Used**	**Treatment And Disposal Option**
Blue	Contaminated glass, medicine voils Metallic body implants	Cardboard boxes	Disinfection using detergent and hypochlorite treatment, autoclaving, microwaving (and then sent for recycling)
Red	Contaminated syringes, tubing, urine bags, bottles, intravenous tubes and sets, catheters and gloves	Non-chlorinated plastic bags/containers	Autoclaving/micro - waving/ hydroclaving (and then sent for registered or authorized recyclers for energy recovery)
White (Translucent)	Any contaminated sharp object	Puncture, Leak, tamper proof containers	Autoclaving/Dry Heat Sterilization followed by shredding or mutilation and sent for final disposal to iron foundries or sanitary landfill or designated concrete waste sharp pit.
Yellow	Anatomical Waste, Items contaminated with blood, Expired or Discarded Medicines, Chemical Waste, Microbiology, Biotechnology and other clinical laboratory waste, human and animal cell cultures used in research	Non-chlorinated plastic bags	Incineration or Plasma Pyrolysis or deep burial

2.4. Special Hazardous Waste

This class of waste includes the radioactive waste, electronic waste, explosive waste.

2.4.1. Radioactive Waste

Radioactive waste defines as the category of waste which includes radioactive materials like plutonium, caesium-137 and strontium-90 etc. Basically the radioactive materials have been used in various fields like nuclear power generation, nuclear research, therapy or medicine based on radioactive materials, rare-earth mining etc and, for health and environmental concern the disposal of radioactive waste is regulated by government agencies. This waste is categorized into three classes i.e., Low-level waste, Intermediate-level waste, and High-level waste. As the name indicates the Low-level waste contains minute amount of radioactive material, with short-lived radioactivity, and includes paper, tools, clothing etc. whereas the Intermediate-level waste contains higher amounts of radioactivity and some requires shielding. High-level waste is highly radioactive and hot due to decay heat, so requires cooling and shielding (Grambow et al., 2016).

2.4.2. Electronic Waste

Electronic wastes are unwanted or discarded electronic appliances which are used in electronic items like refrigerator, air conditioner, television, mixture-grinder, cell phone etc. These waste products contains hazardous components like lead, mercury, cadmium, barium, lithium etc, which causes adverse effect on human health by disfunctioning the various organs i.e., heart, brain, kidney, skeleton etc.

2.4.3. Explosive Waste

Explosive waste includes energetically or chemically unstable devices which can produce a sudden expansion of material that accompanied the production of heat or a large change in pressure.

2.5. Waste Water/Industrial Waste

In the modern world, the technology and science became advance day by day and this leads to come manufacturing age by the startup of the industries. The wastes created by factories, mills, or other industries include gravel, masonry, oil, solvents, and other hazardous chemicals come in class of Industrial waste. Industry pollution takes on many faces like release toxins into air, reduce quality of soil and contamination of water bodies. In this article we focus the industry waste mainly waste water. Water is necessary for humans because all activities of the humans are associated with water. The population growth leads the production of the tons of waste water per day. The textile industries contaminated the water sources by harmful chemicals like, arsenic, lead, organic pollutants etc. which show adverse effect on human health. Many people around the world mainly in developing countries face the problem of lack access to potable water. The facts are glaring, such as 2.1 billion people do not have access to safe drinking water at home (Obotey et al., 2020). The globalization leads the contamination of water bodies as water plays an integral role in all sector of life. For example in the oil refinery industry, the crude oil processing generates about 10 times of wastewater (Pendashteh et al., 2011). According to a report titled SAICE Infrastructure Report Card for South Africa, 2011, an average of 7589 mega liters per day of wastewater is transported across South Africa (SAICE, 2011). All these wastewaters are clean water with contaminants. After efficient treatment of this contaminated water this treated water can be used as a good source of fresh water and solve the problem of water scarcity. (Tetteh et al., 2011).

3. Importance of Waste Management

Waste and population growth both are very serious issue of present era and unfortunately they both are directly proportional to each other. Society has suddenly awakened in the last few years to the dangers caused by the mismanagement of wastes and understood the importance of waste management. The term proper waste management means that the toxic chemicals, harmful substances are filtered or modified in such a way that, they cannot enter into the environment to produce any negative impact. There are several methods of waste management which we discussed in this book chapter.

4. Methods of Waste Management

4.1. Landfill

Landfill is the oldest method of waste management which required discrete space of land that is utilized for dumping of waste material. Landfills are for the most part situated in urban regions where a lot of waste is created and must be dumped in a particular spot. In contrast to an open dump, it is a pit that is dug in the ground. The waste material is disposed and the pit is covered, thus avoiding the reproduction of mosquito, flies and animals which are prone to spread harmful diseases. Landfills may represent a few environmental issues like requirement of land, explosion of hazards, dust etc. however contamination of groundwater by leachate is a major issue. Landfills vary altogether depending upon the waste they get, basically there are three types of landfill - municipal solid waste, industrial waste and hazardous waste. Municipal landfills are natural waste that influences the biogeochemical process in the landfill body and the production of anaerobic leachate with a high content of dissolved salts, organic carbon, ammonium, and natural mixtures and metals delivered from the waste.

4.2. Incineration

This waste treatment process is used for reducing the volume and health risk of non-recyclable solid waste by burning/combustion. Incineration and other different kind of high temperature methods are referred as thermal treatment. Incinerators convert waste materials into steam, gas, heat, and ash and reduce the solid mass by 80%–85%. This reduction percent of solid waste depend upon the composition and degree of recovery of materials such as metals from the ash for recycling.

Fixed grate is the oldest and easier sort of incinerator. Incinerators comes under Waste to energy (WTE) plants, WTE is the broad term which involves burning of waste in a furnace or boiler to generate heat, steam and electricity. Although, incineration is a controversial method of waste disposal due to the emission of gaseous pollutant called flue gas.

4.3. Recovery Techniques

This technique uses waste material (that could not reuse, reduce and recycle) as a precursor to recover the material or energy. This technique has two approaches i.e., waste-to-energy and waste-to material recovery technique. The wastes can be used to recover energy or material via the means of waste transformation using physical, chemical, biological transformations. Incinerator, pyrolysis, gasification are different recovery techniques which produce energy in form of electricity, steam, and fuel etc.

4.4. Recycle Techniques

In this technique, the waste materials are used as raw materials for making new useful products. Mostly the high-density polyethylene recycled waste plastic can utilize for making new products like Plastic bottles for detergent, shampoo, as well as household cleaners. Recycled polyvinyl chloride is used for making resilient and flexible goods such as traffic cones, mud flaps, garden hoses. On the other hand recycled polystyrene is suitable for manufacturing packing cartons. Recycled plastic also used for making trash bags, kitchenware countertops, and carpets. The recycling of biomass leads the formation of fertilizer which is nutrient rich and can be use efficiently in the field of agriculture.

4.5. Plasma Arc Gasification

Plasma gasification is a strategy used for waste disposal or management in which the waste materials turn into valuable products without combustion. This technique uses a combination of high temperature and electricity.

Plasma gasification acquaints high-temperature plasma to decay the waste into its disintegrated form. In the disintegration process, the thermal plasma produced by passing high electric flow through gasification agent. At high temperature, electrons separate from the gasification agent atoms and an ionized gas/plasma stream is obtained. The chemical bonds of the feedstock material breaks with the help of plasma stream, which results into profoundly active electrons, radicals, particles and excited particles in the plasma gasification reactor.

The plasma gasification strategy has advantages like no combustion inside the reactors, lower CO_2 emission and quick response time because of high temperature and high energy density. Due to its fast reaction time high material flow rate can be applied within a compact reactor. The drawback is that it requires high operational cost to create the high temperature plasma.

4.6. Composting

Composting is the controlled decomposition of degradable organic materials such as leaves, grass, food scraps and wastes into stable products by a slow microbial exothermic action.

Composting assists in environmental sustainability, as it aid with holding the soil particles together, in this manner it is preventing soil erosion. It also assists in keeping wastes and waste product in a controlled climate and recycled it into valuable item. They help in the bioremediation of contaminated soil. They also involve in additional increment of biodiversity in the soil by drawing in various fungi, bacteria, insects, etc. that are valuable to the yield of plants. There are different composting methods used for waste management. In Indian-Bangalore Composting method, materials are layered in trench of about a meter deep where night soil and organic residues are put in alternate layers. The pit is at last covered with a 15 to 20 cm thick layer of reject. The materials are left in the composting pit without watering or turning for a quarter of a year. This kind of composting takes around six to eight months to acquire the completed item. This process lays great importance on C/N proportion.

Most of the municipal authorities utilize this technique in India. Again the another composting method which is Indian-Indore Composting method which involves a mixture of raw materials such as plant residues, animal dung and urine, earth, wood ash. Water is layered on the surface of soil 15cm thick to a depth of 1-1.5 meters in a trench or forms a mound above ground called a windrow. Enough quantity of water is sprinkled over the materials in the pit to wet them. Generally, mixture is turned for 2-3 months to provide aerobic surrounding and environment. The process is completed within 4 months. This technique requires intensive-labour and time. It is also prone to flies, wind and pest involvement which can lead to loss of nutrients. Futher the vermicomposting is also used for waste management. In this method of composting earthworms and microorganisms were used, whose joint action provides degradation of organic waste. Vermicomposting requires some specific species that may be adaptable to living in decomposing organic waste rather than in soil. Two species are Eiseniafoetida and Lumbricusrubellus. Earthworms can eat the residue equivalent to their body weight per day. The excreta of the worms—termed “castings”—are rich in nutrients which improve soil fertility. Next composting method is windrow composting. This technique led by putting crude or raw materials in long thin heaps or windrows, which are turned consistently. The windrows are turned or mix on a regular basis to improve oxygen content, to distribute moisture and heat to regulate temperature. A common place windrow composting set up should begin from 3 feet in stature for thick materials like composts and 12 feet high for soft materials.

4.7. Wastes to Energy

Waste to-energy plants consume municipal solid waste (MSW), called as trash or garbage, to deliver steam in a heater that is utilized to generate power as electricity and reduce the amount of waste sent to landfills, which also reduces negative impacts on the environment conditions. There are various kinds of waste-to-energy frameworks or advances. The most well-known sort utilized in the United States is the mass-burn system, where unprocessed MSW is burned in a large incinerator with a boiler and a generator for delivering power in the form of electricity.

WTE can be part into two fundamental classes; the first is thermal and second is biological. The thermal treatment incorporates combustion, gasification and pyrolysis, related methods all of which applied waste to high temperatures but with different oxygen concentration. The second class is Biological– Anaerobic digestion that can be utilized to recuperate energy from wet, biodegradable waste streams. Anaerobic digestion utilizes microorganisms in deliberately controlled conditions to change over biomass into biogas comprising basically of methane and carbon dioxide, and a settled build-up known as digestate.

4.8. Avoidance/Waste Minimization

Waste Minimization is a waste management approach that revolves around diminishing the amount of waste and comprises limiting the waste generation as well as recycling, reuse and treatment. The objective is to minimize the amount of hazardous waste bound for energy recovery, treatment, and disposal facilities. Therefore, waste minimization does not involve treatment processes, which can change the physical, chemical, or biological content of waste.

5. New Insights for Upcycling Waste to Value-Added Products

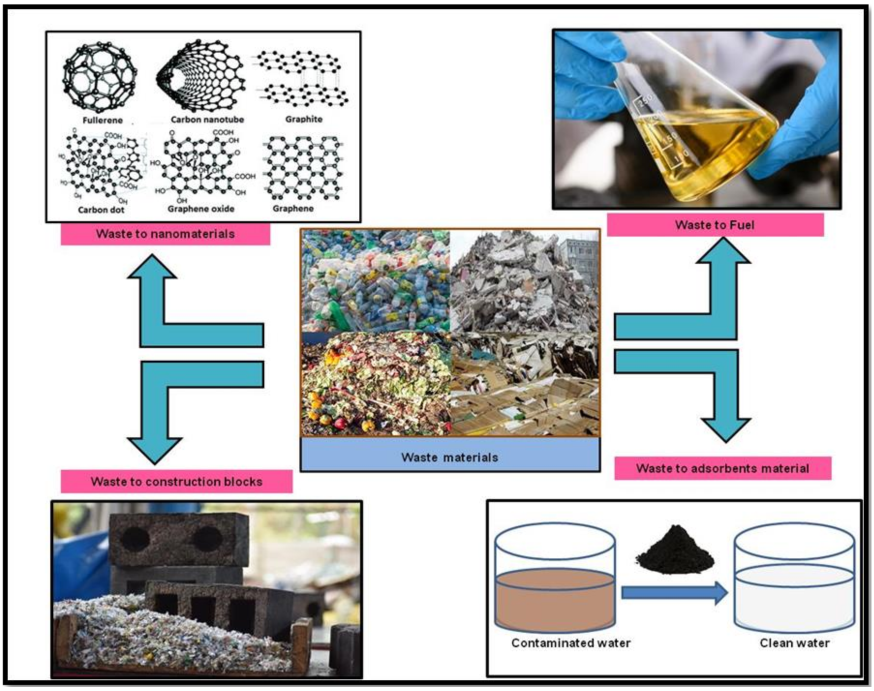

Figure 6. Upcycling of waste into value-added products.

Waste materials create lots of problems which associate with their unmanaged collection and segregation. According to the World Bank report world generate 2.01 billion tonnes of municipal solid waste per year and its approx 33% was not managed via environmentally safe mode. Worldwide 0.74 Kg (varies from 0.11-4.54 Kg) of waste is generated by person per day. The waste generation increases day by day which creates the serious issues in front of scientific community. To solve this problem recently lots of work has been done for upcycling waste to value added product. In this book chapter we focus the upcycling of waste into value added products like fuel, nanomaterials, and concrete additive (Figure 6). Also we highlight the application of waste derived nanomaterial in field of water treatment.

5.1. Waste to Nanomaterials

Nanomaterials are the class of materials which have their size in nanometer range and due to the small size they exhibits extraordinary optical, chemical, and mechanical properties. The present era of research mainly focus on finding the different ways for synthesis of nanomaterials in cost effective and environmental friendly mode, and also find its application in different field of research. Carbon based nanomaterials like graphene, carbon nanotubes, carbon quantum dots, graphene oxide etc have been used but not limited in different field of research like drug delivery, bioimaging, fuel cell, solar cell, supercapacitor and water treatment. The major products of chemical recycling are hydrocarbons, monomers to produce new materials. In recycling process the raw material is quite expensive as it accounts 60-90% of the total production cost and this fact restricts to find new pathway to synthesized value added product in lower cost via recycling.

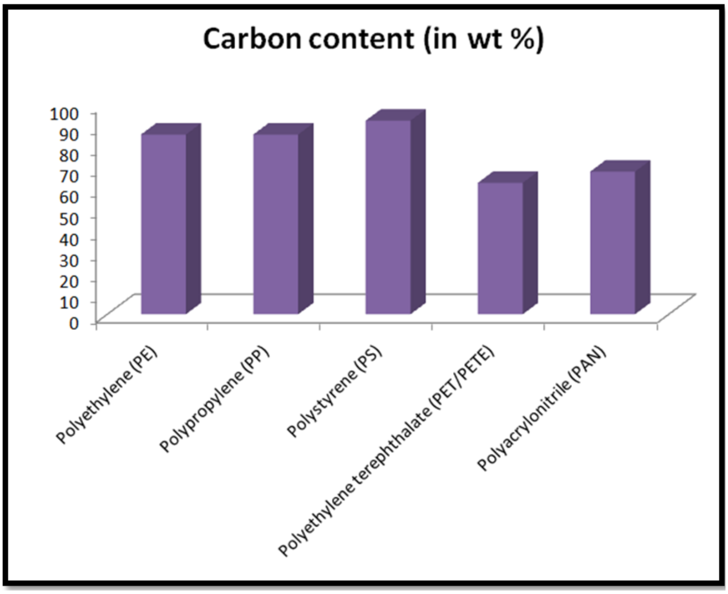

Figure 7. Carbon content in different type of polymers.

In order to solve this issue advanced upcycling process is used now a day in which the quality of final product is upgraded and also the feedstock is cheap like waste materials (agricultural waste, food waste and plastic waste etc).

As this fact is known that plastic is a polymer and it have high carbon content as shown in Figure 7 (Zhuo et al., 2014) and can be used as a precursor for synthesis of carbon based nanomaterials like hydrocarbons (Lovett et al., 1997; Buekens et al., 1998; Yang et al., 2009), carbon black/activated carbon (Esfandiari et al., 2012), carbon fibers (Liu et al., 2012; Norberg et al., 2013), fullerenes (Howard et al., 1991; Richter et al., 1997), carbon nanotubes (Zhuo et al., 2014; Dai et al., 2002; De et al., 2013; Dervishi et al., 2009), and graphene (Tewari et al., 2021; Tewari et al., 2019; Tatrari et al., 2021; Pandey et al., 2019).

Pandey et al., 2019 reported the bulk synthesis of graphene oxide from waste plastic using two step thermal treatments (400°C and 750°C) under nitrogen atmosphere. They use bentonite nanoclay as an intercalating agent in their process. Agricultural waste like oak fruits and oak leaves also used as the source of carbon for synthesis of graphene based materials (Tewari et al., 2019; Tewari et al., 2021; Tatrari et al., 2021) using thermal treatment.

5.2. Waste to Fuel

Energy is a key source of economical growth as energy drives economic productivity and industrial growth. In modern economy the requirement of energy increases day by day while the fossil fuel sources (crude oil, coal, natural gas) depleting and due to this the present rate of economic growth is unsustainable. (Wong et al., 2015)

So it's necessary to find some new routes to generate energy sources. There are lots of papers reported for the upcycling of plastic waste into fuels (Allred et al., 2000; Rangarajan et al., 1998; Gobin et al., 2004; Zhang et al., 2010; Kumar et al., 2011; Hujuri et al., 2011).

Czajczyńska et al., reported the pyrolytic gas obtained from waste tires is good gaseous fuel and a valuable source of energy (Czajczyńska et al., 2017). The municipal waste transforms into gaseous fuel via gasification and co-gasification for energy purpose. The refuse derive fuel can be co-gasified with different biomass/biochar to achieve synergistic effects, to obtain better quality of gaseous fuel than conventional gasification. The common feedstock for gasification includes biomass (Putro et al., 2020; Sittisun et al., 2019), coal (Grabowski et al., 2020), carbonized products (He et al., 2019; Chen et al., 2019), plastics (Nanda and Berruti 2020; Jha et al., 2021), and municipal solid waste (Martínez et al., 2020).

5.3. Waste to Construction Block

The people of present world want to live in the houses made by sustainable materials and somehow this fact is the region of increasing demand of construction materials. The productions of construction materials mainly cement lead the formation of green house gases which negatively impacted the environment and create the serious issue like global warming. On the other hand the rising production of waste and its unorganized management creates the problem. So to find a potential solution of the said issues the researchers use the waste to preparing the construction materials. Recently construction blocks development by using plastic waste (Low-Density Polyethylene) with lower cost has been reported by Monish et al. (Monish et al., 2021).

Waste to usable object: Waste materials are treated such that they can be utilized once more, and the process of such transformation is known as Recycling. Waste plastic is recycled to form different products like chair, tables, recycling bins, plastic bags and many more plastic objects which we used in daily life.

Used and shredded wastepaper and different types of wastepaper items might be used as packaging material or may shape a bit of fertilizer material for soil advancement. At the point when strong waste is used for incineration and heat recuperation, the paper and cardboard substance give a significant part of the energy content that is changed over to heat. Waste cooking oil used in place of virgin oil as a feedstock for biodiesel production is an effective strategy to reduce the material cost in biodiesel production.

We already know about the term composting, composting can also be applied in conversion of waste materials into useful manure like substances which can be used in enrichment of the soil. Organic products, vegetables, dairy items, grains, bread, unbleached paper towels, espresso channels (filters), eggshells, meats and papers can be used in composting. On the off chance that it very well may be eaten or filled in a field or nursery or garden, it tends to be compost.

5.4. Waste to Adsorbents Material

Rapid pace of population expansion, unplanned urbanization, and industrialization have largely contributed to water pollution and soil of surrounding. Adsorbents design for the purpose of waste water treatment gets disposed to landfill and this action causes adverse effect to the environment due to the presence of inorganic impurities within the adsorbents (Nasruddin et al., 2018). Fresh water bodies get polluted due to dumping of untreated sanitation, toxic industrial waste and runoff from the agricultural sector. In developing countries children and women are more susceptible to disease (70 to 80%) related to water contamination (Zwain, et al., 2014).

Now it is essential to search the new route for development of smartest materials in a thrifty way which acts as adsorbents for removal of pollutants present in waste water. Nanomaterial based adsorbent have tremendous adsorption capacity but the high cost of nanomaterials limits its application. To solve this issue research focus on finding new route for synthesis of nanomaterials in economical manner and for that they chose cheap precursor like waste material (waste plastic, agricultural waste). Activated carbon synthesized by corn cobs via physical activation methods with CO_2 and steam at high temperature of 1173 K shows its utility for removal of methylene blue dye (100 mg/g) and follow Langmuir adsorption isotherm (Reddy et al., 2016). The solid demolition waste i.e., bricks upcycled into LDH-ABM (layered double hydroxides-activated brick mass) which act as a promising candidate for tellurium extraction from photovoltaic waste (Chen, et. al., 2021). Elias et al., reported the use of palm oil industrial residues as empty fruit bunch-activated carbon for removal of lead from water at maximum concentration 92.24 mg/L under the optimum condition i.e., 10 g/L of adsorbent, pH 1.0 and 15 min as contact time (Elias et al., 2021).

6. Significance of Waste Upcycled Nanomaterials for Water Remediation

The source of energy and life is fresh water, but unfortunately there is a shortage of clean fresh water worldwide and millions of people are suffering from the same. The research reveal that 70% of diseases caused by consumption of unsafe water. The water bodies mainly contaminated by heavy metals (Zn, Cd, Hg, Pb, Cr, Cu,) and consumption of this contaminated water leads to the serious issues like liver damage, nerves and blockage of functional groups of vital enzymes and bones. The rapid development of industrial activities is the major reason for increasing heavy metals level in water system. To purify the water and make it suitable for drinking purpose adsorption is economically appropriate method. Different adsorbent have been reported in last decade for removal of different impurities present in water. Here in this book chapter we only focus the nano adsorbent which is synthesized by using waste materials (Sud et al., 2008). Kazak, et al., reported synthesis of microporous activated carbon from vinasse using KOH activation with high surface area (1042 m^2/g) which shows its utility for removal of Victoria Blue B as model dye (Kazak, et al., 2018). Motivated by the significant scope of waste to wealth researchers performed lots of work to generate value-added products from agricultural waste materials for water remediation. To purge the heavy metals (Cu, Zn, Pb, Cd, Ni, As etc.) from the water lots of waste generated value added products were reported by the researchers (Kazak, et al., 2018, Asim et al., 2020). Asim et. al., 2020 reported the use of coconut coil as precursor to develop the environmental friendly absorbent for Cu removal. Waste materials can be managed and converted into useful products like wastewater adsorbents in different forms such as (i) biochar/activated carbon, (ii) sorbent, or (iii) gel-form. Heavy metals such as Ni, Co, and Pb can be efficiently removed from polluted water using silica gel. The high amount of silicon in ash of agricultural residue supports the formation of silica gel for waste water treatment. Silica gel is the waste material that converted into ash by combustion or carbonization process and after chemical treatment ash turn into gel in which acid/ base concentration, reaction time, temperature, and pH, are significant factors which can vary for different types of waste materials (Gad et al., 2016; Conradi et al., 2019; Tahan Latibari et al., 2013). The activated carbon and graphene based nanomaterials produced by pyrolysis of waste materials at high temperature range. This temperature range varies and depends on the nature of waste which used as a precursor. Generally for agricultural waste the pyrolysis temperature range (475°C-600°C) is lower while for plastic waste the temperature is higher i.e., 800°C-950°C (Satayeva et al., 2018; Pandey et al., 2019). In inert environment using microwave pyrolysis (600°C) biochar can be produced within 15 to 20 min from waste material (Shukla et al., 2019).

The absorbents have somehow lost its adsorption capacity after many cycles of regeneration and application, and these waste adsorbents can converted into valuable products like cementitious materials, fertilizers for soil nourishment, and biofuel via pyrolysis, hydrothermal carbonization, and gasification (Chandra Paul et al., 2019; Muhmood et al., 2019). On the other hand, the natural waste resources can be chemically treated and incorporated with nanoparticles to enhance the sorption efficiency (Aydin et al., 2019).

Also the graphene based nanomaterials are excellent candidate for water remediation and scores of papers reported for synthesis of graphene based nanomaterial for water treatment. On the other hand research reveal that iron based catalyst are better for preparation of graphene like Biochar. Also the composites with graphene show superior properties in comparison to the parental materials for heavy metal removal because the presence of multiple electron donors on graphene surface.

Populus caspica wastes were reduced to multi-layer green graphene and then post-modified with aluminum/iron for fluoride amputation (Talebi et. al., 2021; Fang, et al., 2020.).

7. Present and Future Challenges

In this modern time people wants to make their life easy and for that they are very much dependent on the electric machinery which basically contain polymers (plastic) and metals (iron, alloys). The use of these objects increases day by day which leads the increasing demand of these objects. As the technology try to set the new goal every time the companies launched the new electronic products in the market and people are buying them to maintain their standard or making their life easier and this thing generates lots of electronic waste which creates serious issue.

So there is need to develop the strategy for waste segregation and management, also the upcycling of waste into value added products is excellent means to solve the global issue of waste. Nanomaterials synthesized by using different waste materials can be used as adsorbents for the removal of various pollutants present in wastewater. The adsorption is a suitable technique for the economical aspect as it is cost-effective and easy over the other purification techniques but the used adsorbents have been disposed to the environment which negatively impacts the soil and environment. So to solve this, it is necessary to utilize this waste adsorbent material for other applications. The bio-adsorbents used for removal of ammonia and phosphorus, can be further utilized for soil nourishment (Hossain, 2019; Shukla et al., 2019). Adsorbent which used for removal of hazardous heavy metals, microplastics, PFAs components can be utilize as cement supplements (Marthong, 2012). The bio-adsorbents with high carbon content can be applied to produce biofuel, other petroleum-based fossil fuels (Hossain et al., 2020). Previous studies reported that the biomass handling industries can produce bio-oil via hydrothermal carbonization and fast pyrolysis (Hossain et al., 2020). In addition, the produced bio-oil from waste is more eco-friendly over crude oil (Rahman et al., 2015). The nature of the adsorbent plays an important role in finding its application for the removal of various types of contaminants as it depends on the nature of the adsorbate. An incorporated approach is needed for adsorbents derived from waste, so that waste can be applied in different applications and pilot scale plant can be designed in future to solve waste problem.

A broad interpretation of the overall process is necessary to find its utility on an industrial scale and for that, the process and material should be economically favorable. The small or plant scale integrated approach with attractive attributes, can be extended for commercial purpose but they face some significant challenges. The main challenges appear due to the mixing of different types of waste materials which leads to the problem of finding the adsorption capacity of the synthesized adsorbent material as the adsorption capacity of different materials varies widely.

Selection of waste materials is also very challenging as it depend on the geographical location, climate and waste production rate. The variation of composition of waste leads the flexible adsorbent properties. The more research is required to develop the classification methods for the waste.

Till the present date there are lots of experimental data available to convert waste to value-added product in lab or large scale for different applications. But it is very important to have an integrated, detailed experimental analysis for checking the large scale feasibility of the process/ materials.

CONCLUSION

This book chapter provides an overview regarding the classification of waste, importance of waste management, waste management approaches, new insights for upcycling waste to value-added nanomaterials, significance of waste derived nanomaterials for water remediation, and also the present and future challenges associated with waste management. This chapter also introduced the potential of waste materials in field of water purification. Up conversion of waste into value added products open the new path which can play an important role in waste segregation and management. The nanomaterials (adsorbents) generated by the pyrolysis, carbonization, other thermal treatment of the waste can effectively remove the pollutant from water. The synthesis and use of these materials/concepts is still confined to the laboratory scale and its implementation is still challenging for plant or large scale. The use of waste as a raw material draws more attraction for industrial implementation due to the continuous availability of waste. On the other hand, this chapter emphasized the significance of reuse of the waste adsorbent for various applications. Also the wastewater industries need to be proactive and evaluate the benefits of waste materials to implement the concept into real practice.

If the concept of waste to wealth (waste to value-added product for water remediation) can applied in real practice, the waste water treatment agencies can play a vital role for waste management with using cost-effective materials. In future the specific policies implementation by government can make this concept successful and bring long-term benefits for environment, economy and society as a whole.

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Chapter 3

WASTE: PROBLEM, SUSTAINABLE MANAGEMENT, AND CONVERSION TO VALUE ADDED PRODUCTS

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ABSTRACT

The simple definition of waste is something that ceases to be of its intended use. It can be more generalized in other terms by defining it as something that has been thrown away and found in garbage i.e., discarded after its primary use, which is either defective, worthless, and has lost its value. But in the era of sustainable development, where humanity has come to understand that not only the natural resources available on the planet are limited but are also non renewable with this understanding gaining more and more and more momentum the waste being generated has acquired an important role and has generated higher interest towards conservation of the available limited natural resources if not addressed are bound to have an adverse effect on our environment, ecosystem as well geological system. Before thinking of seeking benefits from waste, management of disposal, their degradability should be importantly considered. For the

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sake of saving, it can be broadly divided into two categories i.e., biodegradable and non-biodegradable waste while the former may not have many serious lingering harmful effects in the long run on our environment as eventually they will be taken care of by the nature itself. It is the latter that we need to focus upon to reduce manage and where ever possible reuse. Further, to understand the concept of conversion of waste to value-added products and waste management we need to gather specific knowledge of types of waste, their source of generation, and problem associated with different types of wastes. Therefore, in the present chapter, we will briefly review these facts to theorize the understanding of waste, its type and management to arrive at a solution for benefit of the society. With the motto of 3R's (Reduce, Recycle, Reuse) which also can help in the generation of wealth from waste, if done, can incentivize the interest in better management of waste being generated making the process self-sustainable in long run by generating some income in the process.

Keywords: waste, waste management, sustainable development, nanoscience, environment, 3R's, bio-degradation

1. Introduction

Waste can be defined in many ways, in a simple manner; it can be conceptualized as "material that is unwanted by its user" or manufacturer alike i.e., simply a by-product of any production process, for example, fly ash produces from a furnace (Demirbas 2011; Guerrero et al. 2013). Alternatively, it can be a product whose inherent value has been consumed by the perspective producer/consumer – for example, a newspaper that has been read, opened and emptied a package of chips/biscuits, banana, orange peels, etc. all come under the category of waste from the perspective of its consumer. So, after becoming waste for the consumer i.e., by losing its inherent value the most viable option or perhaps the only available option with a consumer is to permanently dispose of it. Now, this waste is then collected by a waste disposal services provider who acts as an agent and dumps this discard at the dumping point. However, the material that may be waste from the perspective of someone can have a value for someone else i.e., the newspaper can be used as an input at a pulp and paper plant or fruits/vegetable peels can be used as a composter no matter how insignificant the value may be. So, the waste disposable services provider may manage to divert waste to different streams depending upon where they can be re-monitized. To convert waste value addition can be achieved, thus value can be reintroduced to the waste through some kind of sorting/treatment, etc. For example, the collected newspapers may be taken to a Material Recycling Facility (MRF) where they are sorted, bundled, and compacted to make packets, some decorative marketable (valuable) product packaging materials such as corrugated boxes which know in this form have inherent value to its prospective buyer. In this way, we can reuse the waste to good value products (Memon 2010; Pariatamby and Fauziah 2014). But, if we look around as, huge waste is always around us as shown in Figure 1. This is so because; waste is an unavoidable by-product of most human activities. Therefore, cities of developing countries like India as well as of developed countries like US, Australia, etc. are now struggling with the problems of high volumes of waste dumped around them. Only the huge dumped volume is not the problem, rather, the costs involved in managing it, the technologies and methodologies involved in disposing of it are other major issues, however, the impact of wastes on the local and global environment is another typical problem which is of major concern (Shekdar 2009).

Figure 1. Images of huge waste dumping yards in developed and developing countries. Ref: hindustantimes.com; ecowatch.com; alamy.com, nytimes.com.

Nevertheless, management of different waste streams is a huge problem but it's the right time to find out a window of the solution by concentrating on the source of its creation itself i.e., the consumers i.e., community as well as the manufacturing sectors to inculcate behaviour changes and awareness and evolve innovative technologies for disposal of waste being generated, stress upon effective management of the waste on one hand. While on the other hand also a need for a simplistic approach in lifestyle expanding consumerism, our greed which brings a revolution in the industry for making our life easy living, ever increasing demand of assets by communities. This also increases the necessity to burn fossil fuels to match the supply and demand, resulting in the release of enormous amounts of greenhouse gas which continuously polluting our atmosphere resulting in a change in climate the situation has been compounded further by the destruction of forests. Consequently, the planet is warming, leading to the melting of polar ice caps, posing a grave danger for many low-lying lands with the risk of disappearing from the face of the earth altogether. Nowadays, these issues have been amply demonstrated in goals of sustainable development and adopted by good practices from many cities around the world (Ferronato and Torretta 2019).

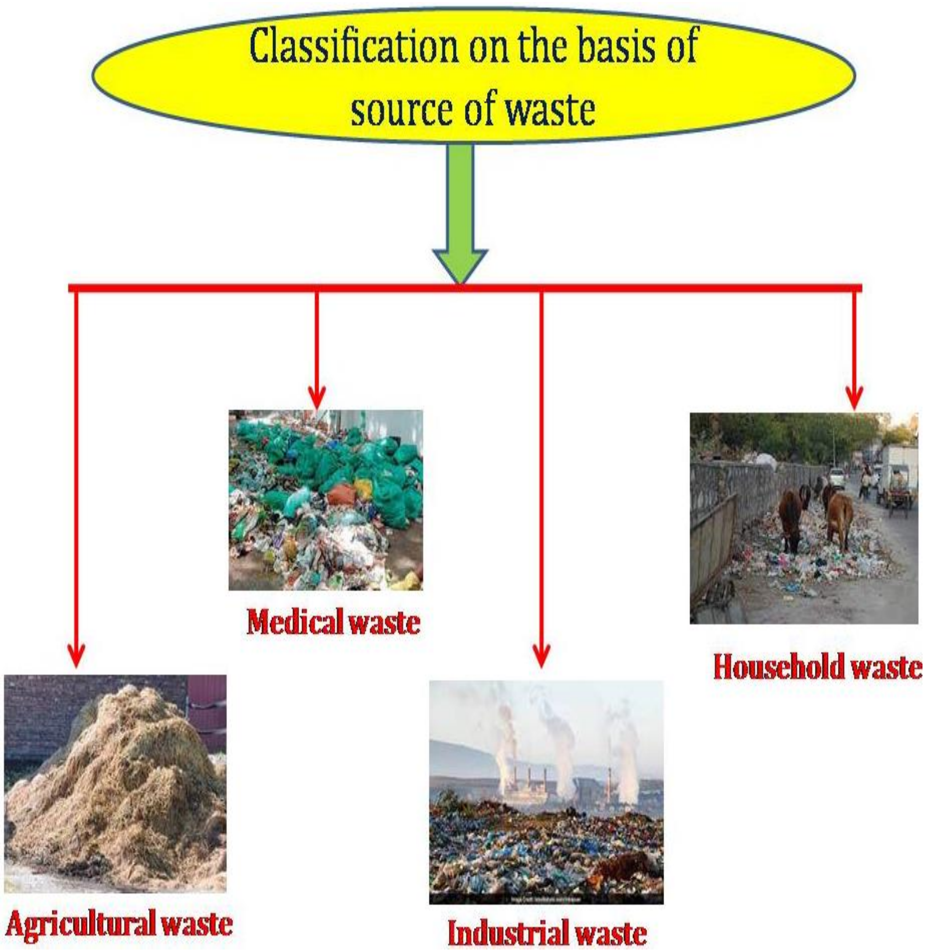

Figure 2. Schematic of different waste based on sources.

With this brief introduction, in this chapter, we will discuss the classification, problem, sustainable management. and conversion to value-added products, which poses formidable challenges to both developed and undeveloped countries of the region along with developing countries in the world.

2. Classification of Waste

There may be so many ways to classify waste. Typically, the waste streams can be classified based on their sources. Thus, the majorly types of waste are agricultural waste, medical waste, industrial waste, and household waste. Such classification is schematically discussed below.

2.1. Agricultural Waste

Agricultural waste is generated from the different approaches involved in the process of various agricultural activities. Chemical used as fertilizer in the crops, harvesting waste involved in the agricultural activity during the processing of crops, etc. It also includes the waste coming from poultry farms, dairy, agricultural farms. Fertilizer used in the agricultural activity is one of the major sources of waste, which causes pollution in the local water sources and soils. Pesticides and chemicals are also contributing in agricultural waste (Obi et al. 2016; Duque-Acevedo et al. 2020).

2.2. Medical Waste

It is a solid waste that is generated during the diagnosis, treatment, or immunization of humans. Hospitals, physician practices, dental practices, blood banks, and veterinary hospitals/clinics are the major sources of medical waste (Windfeld and Brooks 2015). This also includes medical research facility, and laboratory involved in the medical facility, human/animal tissue, blood-soaked bandages, surgical gloves, cultures, stocks, or swabs that were used to inoculate cultures (Cheng et al. 2009).

2.3. Industry Waste

The waste from industry may be in any form i.e., solids, liquids and gases. The major sources of industrial waste are the power generation plant to meet the daily power supply, metal processing units, cement industry, iron and steel manufacturing plants, manufacturing of leather materials, food packaging, chemical transports equipment, resin and plastic manufacturing industries. The water treatment plants have also come under the category of industrial waste (Bonton et al. 2012). The liquid generated and gases emitted during the manufacturing of industrial products cause the pollution of underground water and river water and gases pollute the local environment. The power plants based on coal produces ash in large amounts also comes under the category of industrial waste (Goodarzi 2006).

2.4. Household Waste

Household waste is any waste generated from discarded material from the houses. The material used daily in the kitchen comes under the category of organic waste, which is not harmful. The discarded material from the household like plastic, metal, chemicals, batteries, and electronic waste comes under the category of inorganic waste of household. The discarded mattresses and furniture form a major component of the household. Household waste like chemicals, batteries, plastic, and metal enhances the pollution in local sources of water and nearby environment (Choe and Fraser 1991; Verma et al. 2016; Bassi et al. 2017).

Figure 3. Waste harming to lives and environment on earth. Ref: britannica.com, onegreenplant.org, nationalgeographic.org, dolphinproject.com.

3. Problem Generated with Waste

It is good the advancement in technology helps in economic development in raising living standards all over the world, which makes our life simpler to run on day to day basis, but this adversely, affects our environment and has disturbed our ecosystem (Rawat and Agarwal 2015). This causes the problem which now a day's is beyond the handling capacities of urban governments and agencies. In the Asia and Pacific Region especially, there is a huge increase in the quantity and complexity of generated waste (Pariatamby and Fauziah 2014; Zurbrugg 2002). Whilst to these, industrial diversification added substantial quantities of the industrial hazardous waste which are directly drained out in nearby land or pond/lake. Also, improper management of the healthcare facilities leads to huge biomedical waste into the waste stream. All such waste stream severely affects the environmental and human health consequences. The world is facing huge environmental issues for the last couple of years majorly due to the huge production, miss-management and distribution of waste materials such as plastic waste, tyre waste, and agriculture waste. The foremost challenges are associated with waste generation and scarcity in waste collection, transportation, and management and dumping. The waste materials have such huge and vast environmental effects that are certainly causing depletion of breathing air quality, rise in global temperature, earth erosion, flood, and other environmental calamities also including being a crucial factor for spread and germination of several deadly diseases. Figure 3, is depicting the photographs captured from different sites showing the alarming situation of unplanned generation and unmanaged wastes which potentially hazard our environment and other lives on earth. "*According to the Environment Program of the United Nations (UNEP), nearly 11.2 billion tons of solid waste is generated every year, which is a significant source of environmental degradation and negative health impacts, particularly in low-income countries, where more than 90% of waste is openly dumped or burned (UNEP, 2020)*". This situation is alarming thus forced to think towards the development, implementation, and strengthening of different policy strategies to resolve it (El-Fadel et al. 1997; Narayana 2009; Singh et al. 2011)).

But this is the right time to find out a solution through innovation in technology for finding proper disposal method, evolving revolution to convert the waste into some value-added products, production and use of biodegradable materials. As we are living in the era of nanotechnology so the best way is to find a solution for managing waste either in their conversion or disposal through a methodology that involves nanoscience and nanotechnology (Pappu et al. 2007; Singh et al. 2011).

4. Nanotechnology as Solution to Waste

With the increase of waste generation and the problem of not properly managing it, the focal challenge that the Human race is facing these days is related to the protection of our ecosystem. Over the years, just for the sake of simplifying our lives, humans developed the number of technologies for which we have intentionally and unintentionally shattered our atmosphere by polluting air and waterways by overuse and discarding of plastics and human-made creations, continuous mining and burning of fossil fuels has contributed vastly to climate change, melting of our glaciers, holes in ozone protection, etc. Now is time to use the same advancement in technology to repair our mother earth and re-invent our relationship with mutual respect, for which we need to utilize the tools of nanotechnology to set into motion and play an imperative role in protecting our planet for the future in a sustainable way. That said, the question arises: How nanotechnology can help us to protect the earth from the enormous amounts of waste being generated. *Nanotechnology is the manipulation of matter at the nanoscale (*Bhattacharyya et al. *2009).* As it is well-known fact now that "*nanomaterials exhibit unexpected properties compared to their bulk counterparts; their high surface-area-to-volume ratio imparts unique physiochemical properties, including versatile functionalities and enhanced reactivity or selectivity".* Nanoscale materials like an array of inorganic nanocrystal-based electrocatalysts have potentially shown an economical and environmentally compassionate light-harvesting stable system for photochemical hydrogen production (Nasrollahzadeh et al. 2019; Poole and Owens 2005). Also, conversion of generated waste into some nanomaterials which become value-added products can be a better solution for saving raw materials as precursor reagents i.e., utilizing the nanotechnology's unique attributes as producers of waste to wealth. This will help in managing the danger of waste dumping to our ecosystem, in decreasing greenhouse gases that could undoubtedly lead to the protection of our environment and climate (Mobasser and Firoozi 2016; Taran et al. 2021).

Industrial wastes bring huge amounts of toxic gases and oil spills other than solid waste which can be catastrophic for oceans, rivers, wildlife, and even for the population that reside within nearby regions. The use of air filters, chimneys, and methods of clearing spillages are inadequate and have become conventional. Nanotechnology may provide adequate solutions for this and can contribute to the superiority, ease of use, and feasibility in several ways (Jassby et al. 2018).

4.1. Nanotechnology as a Solution for Water Disinfection

Use of nano-grid of photo-catalytic copper tungsten oxide nanoparticles, these grids when exposed to sunlight it smashes down oil into biodegradable compounds. This grid of photo-catalytic nanoparticles exploits the entire solar spectrum and can work in water for a long time. Nanotechnology could help us in the fabrication of nano-sized membranes for purification and desalinization process thus provides better means of eliminating, decreasing, or deactivating of water contaminants. Nanotechnology can help in producing better chemical and biological sensors for the detection of pesticides, heavy metals, toxic agents, etc. Nanotechnology can be used as "pollution prevention" technology as it can help in sensing not just pollutants, but also waterborne or airborne communicable diseases. For example, the use of nanoparticles of Ag and TiO_2 based catalysts for photocatalytic disinfection are alternatives for chlorine-based biocides. The use of iron nanoparticles for removing organic solvents in groundwater is already in practice. The process of dispersing nanoparticles into the water to decompose the organic solvents without the need of pumping out water from different sites makes the process of cleaning and disinfection process more efficient and cost-effective. Nanotechnology can also provide the solution to eliminate radioactive waste: nano-fibers of *titanate* act as good absorbents for radioactive ions such as cesium and iodine thus help in water cleaning purposes (Theron et al. 2008; Gehrke et al. 2015).

4.2. Nanotechnology as a Solution for Air Purification

Carbon dioxide (CO_2) produced from the burning of fossil fuels, exits from industries in a number of manners perhaps, coal mining, etc. is the prime threat to the environment. The use of renewable energy resources is already a solution for reducing the release of huge amounts of CO_2. However, dumping, decomposing the waste also produces the CO_2 so there is a need to filter, capture and storage of CO_2 thus generated, in case there is no viable alternative to burning them. The currents methods which are used to separate CO_2 from other gases produced from burning are very expensive, utilize chemicals, and are not competitive enough for large-scale applications. However, utilizing the membranes constructed out of nanomaterials could work better, at a low cost, and without the aid of additional harmful chemicals. Such membranes could be used to treat large gas streams under low pressure (Hosseini et al. 2007). Other by-products like volatile organic compounds contributing to smog and high ozone levels thus are also hazardous to air quality. Nano-catalysts made from porous manganese oxide with gold nanoparticles are capable of removing volatile organic compounds as well as other toxic acids from the air at ambient temperatures (Sinha et al. 2007).

5. Nanoparticles from Waste: 3R's of Sustainable Goals

The alarming environmental challenges faced due to waste generation, collection, shifting, treatment, and disposal (Kumar et al. 2017) that the world is facing is increasing at an exponential rate coupled with rise in population day by day. Due to which the volume of waste generated is also growing which affects both public and the environment badly. Therefore, as discussed above nanotechnology is one of the best solutions which can be associated with waste management. The use of nanotechnology is emerging as a potential solution to all the problems relating to the environment and waste management (Taran et al. 2021). Nanotechnology includes those technologies which execute at nanometer scale for various applications. Nanotechnology innovative materials possess a very high surface area which increases the reactivity of the material and change in physical properties also. The increased surface area of nanoparticles makes the adsorption process a highly suited process which can be used in water purification, gas purification, sensing application, energy storage application (Ali and Hassaan 2017). A new option on the conception of generating nanoparticles from reprocessing the waste has been recently acquired a lot of interest. It works on the concept of **3R**'s of sustainable goals i.e., **R**educe, **R**ecycle, **and Reuse**. Rising prices for raw materials and energy, coupled with the increasing environmental awareness of consumers, are responsible for a flood of products on the market that promises certain advantages for environmental and climate protection. Nanomaterials exhibit special physical and chemical properties that make them interesting for novel, environmentally friendly products.

Examples include the increased durability of materials against mechanical stress or weathering, helping to increase the useful life of a product; nanotechnology-based dirt- and water-resistant coatings to reduce cleaning efforts; novel insulation materials to improve the energy efficiency of buildings; adding nanoparticles to a material to reduce weight and save energy during transport.

In the chemical industry, nanomaterials are applied based on their special catalytic properties to boost energy and resource efficiency. Nanomaterials can replace environmentally problematic chemicals in certain fields of applications (Vinu and Madras 2010).

Different waste materials have been used as an initial feedstock for synthesizing nanomaterials. Researchers have adopted different methods and used different materials to get value-added products from wastes. Lots of literature is available in this context.

Carbon nanodots (<10 nm) are created from waste plastic bags by cutting them into small pieces and heating them at high temperature in a solution of Hydrogen Peroxide (H2O2) and household bleach. They show fascinating optical properties and potential in imaging applications (Aji et al. 2018).

Silicon carbide nanoparticles have been created from heating the unused compact discs (CDs) one of the E'waste in the urban area along with some sand. The so produced nanoparticles depict extraordinary thermal, chemical, and mechanical stability (Rajarao et al. 2014).

Glass is one of the common household waste products that accumulate in tons of our landfills. It is commonly named as silica, a mixture of silicon and oxygen. A research group at UC Riverside has converted silica into silicon nanomaterials. They proposed the use of so produced Si nanomaterials in energy storage applications i.e., in lithium-ion fuel cell batteries for vehicles. They crushed glass into small pieces followed by cleaning it with isopropyl alcohol and mixed it with a reducing agent. They heated this mixture in a furnace at high temperature in the presence of magnesium, to produce silicon nanoparticles (Li et al. 2017).

Batteries use heavy metals like mercury, lead, cadmium, and nickel, which are toxic to aquatic life, human beings, soil, and vegetation. So, can create hazards if not decomposed properly. Batteries are one of the essentials parts of our daily life, we use them for remote operation, in watches, Inverters, laptops, and in other consumer electronics applications, therefore, one can imagine how much landfills waste are created every day from the batteries themselves. Extracting cathode material from waste batteries can be recycled and reused for different purposes (Bandi et al. 2019; Piana et al. 2020).

The use of Hydrogen-powered technologies is one of the environmentally friendly technologies which can help to save our natural resources. But producing hydrogen is mostly carrying production carbon dioxide, which loses the purpose of a sustainable environment. Through nanotechnology, we can light up the green glow in producing hydrogen fuel. For example, titanium dioxide (TiO_2), is a common white pigment in its bulk form, when reduced to nano-size shows enhanced photocatalytic activity - the ability to convert photon into energy which decomposes the water molecules into hydrogen and oxygen i.e., water splitting. Therefore, use of renewable energy electrolysis process split water into hydrogen and oxygen offers clean and green energy storage devices that may portable too and durable (Ni et al. 2007).

Utilizing agricultural wastes to produce nano-sized cellulose materials is also a current trend in biological sciences and can be used as better biocides (Hu et al. 2017). There are two main groups of nano-celluloses (NC): nano-fibrillated cellulose (NFC) and cellular nano-crystals (CNC). They are often known as 2nd generation renewable resources for oil products. They possess properties like low density and high mechanical properties, renewability, and biogas characteristics which seek more attention (Singh and Singh 2013; Ventura-Cruz and Tecante 2021).

The silica nanoparticles are having multifaceted applications; however, their production method is very complex and requires elevated temperature. Researchers have used a simple carbo-thermal reduction method to convert plastic waste, disposable boxes, and water bottles to produce silica nanoparticles of different sizes (Salomo et al. 2018).

Agricultural wastes are generated and disposed of indiscriminately in the environment and thus pose many environmental challenges. Through some acid treatment and fermentation process, they can be converted into valuable products. Extracting some agricultural waste like cassava periderm, corn stalk, rice straw, rice husk, leaves of bamboo, and cob into potential sources of silicon nanoparticles have been explored which can be used for photovoltaic application (Adebisi et al. 2017; Farirai et al. 2021).

Waste or by-product of the seafood industry, Cockle shells can be used to make calcium carbonate nanoparticles using an eco-friendly method (Islam et al. 2013). Simple grinding and milling of the shells synthesized nanoparticles with a composition of 99.5% $CaCO_3$. Results have shown that the pure nanoparticles resulted in $CaCO_3$ aragonite polymorphs of approximately 78 nm. The NPs have great potential to be used as urea biosensors due to their ability to immobilize urease enzymes on their large surface area. The NPs are primarily functionalized with acrylic acid Nhydroxysuccinimide ester. The succinimide group binds to the amino group of the enzyme. Approximately 85.8% of the urease can be successfully immobilized on the large surface area of the as evidenced by Bradford protein assay (Zhu et al. 2020).

From waste masks, finger-like carbon material and rod-like CuO nanoparticles and were obtained which were used as modification agents for glassy carbon electrode (GCE). The modified glassy carbon electrode (GCE) is used to develop the voltammetric method for the detection of pazopanib, tyrosine kinase inhibitor. The method worked excellently at nano-detection levels. The carbon material has a core-shell structure which increases its electrical conductivity (Bilge et al. 2021).

Silver and gold NPs of different shapes and sizes depending upon various experimental parameters can be synthesized from fruit wastes (Francis et al. 2017). The synthetic strategy avoids the use of toxic solvents and chemicals. The NPs can be applied against foodborne pathogens due to their antimicrobial activity (Ali et al. 2021).

Nanomolar concentration of glucose can be detected using an electrochemical sensor based on multi-walled carbon nanotube (MWCNT) and nano X zeolite as a substrate for AuNi bimetallic nanoparticles obtained from agro-waste (Amiripour et al. 2021).

Jack fruit (Artocarpus heterophyllus) peel extract can be used for making iron NPs (FeNPs-JF) which consist of zero-valent NPs (nZVI) alongwith oxyhydride and iron oxides. The NPs can be used for the industrial dye waste water remediation thus helping in waste minimization and solid waste management. They serve as heterogeneous Fenton-like catalysts for the degradation of Fuchsin Basic, a pollutant dye, through a surface-chemical reaction (Jain et al. 2021).

Zinc oxide nanoparticles of good particle size can be synthesized from the waste of pineapple pericarp or peels. The non-toxic NPs of good purity and good size can be used for wastewater treatment. They have particle sizes 10- 60 nm, consist of various functional groups like phenol, olefins, aldehyde, and are coated by the biological material. The plant-assisted NPs can be used for the treatment of textile effluent by assessing Chemical oxygen demand (COD), total suspended solids, dissolved oxygen (DO), total dissolved solid (TDS), turbidity, and conductivity (Mirgane et al. 2021).

Waste aluminium foil is used for the synthesis of aluminium oxide nanoparticles which were, in turn, used for the fabrication of aluminium-ion cells. The NPs were synthesized by co-precipitation of aluminium foils at constant annealing room temperature followed by mechanical milling to nanoparticulate range. Thus, waste aluminium which is found in abundance in landfills can become a part of energy storage devices (Nduni et al. 2021).

Some more related reports are reviewed here. Alonso et al. used waste sulfonated polystyrene to utilize them as a catalyst in different reactions (in biomass valorization reactions, biodiesel synthesis) (Alonso-Fagúndez et al. 2014). Xiu and Zhang (2009) extracted Cu from waste printed circuit boards and then were used as a catalyst to improve the photocatalytic performance of TiO_2 to degrade toxic organic dyes. Shankar et al. (2016) used rice husk to synthesize silica nanoparticles and used them in energy storage applications and drug delivery. Various biomass wastes such as bamboo waste, rotten potatoes, tobacco waste, tea waste, etc. are used in supercapacitor applications (Chen et al. 2016; Chen et al. 2017; Song et al. 2019; Yang et al. 2014). Park et al. (2014) synthesized carbon nanodots from food waste and used them in the bio-imaging applications. Hu et al. (2014) used carbon nanoparticles as a fluorescence probes in detection of Fe ions.

Hassan et al. (2013) has derived $CaCO_3$ nanoparticles from waste eggshells and then Roy et al. (2019) used those nanoparticles as fillers in natural rubber to enhance the thermal and mechanical properties of natural rubber. Sankar et al. (2019) derived spherical activated carbon nanoparticles from tea wastes and also used them in lithium-ion batteries. Lu et al. (2012) used pomelo peel waste to produce carbon nanoparticles. Li et al. (2016) have derived carbon black nanoparticles from waste tyre rubbers via a light pyrolysis process. Pandey et al. (2021) used waste candle soot for the production of carbon nanoparticles. Hu et al. (2014) used waste plastic bags for the synthesis of carbon nanoparticles. Jain and Tripathi (2015) used sugarcane waste to produce nano activated carbon. Al-Rahbi and Williams (2016) used tire waste to produce nano-activated carbon. Yao et al. (2020) used the waste fish scale for the synthesis of carbon nanoparticles for the sensing of ferric ions. Different wastes are used for synthesis of silver nanoparticles such as pineapple waste (Agnihotri et al. 2018), mango peel extract (Yang and Li 2013), cashew nutshell (Velmurugan et al. 2014), onion peels (Santhosh et al. 2020), banana peel extract (Bankar et al. 2010), pomegranate fruit peel to reduce gold and silver ions to form gold nanoparticles and silver nanoparticles (Ahmad et al. 2012). Yuvakkumar et al. (2014) used rambutan peels to synthesize zinc oxide nanocrystals and nickel oxide nanocrystals (Yuvakkumar et al. 2014). Prasad et al. (2016) used watermelon rinds for Fe_3O_4 magnetic nanoparticles whereas Lakshmipathey et al. (2015) used watermelon rinds for the synthesis of palladium nanoparticles. Kumar et al. (2015) used mineral waste collected from iron ore processing plants for the synthesis of magnetite nanoparticles. Rao et al. (2015) used orange peel waste to collect TiO_2 nanoparticles.

6. NANOTECHNOLOGY AS A SOLUTION NOT FURTHER HARM

Nanotechnology offers the colossal prospects for implementation in environmental technologies. There are many success stories of nanotechnology for saving our environment like numerous sensors for monitoring the air quality, methods of toxic gas adsorption, water disinfection, etc. However, to balance with the current needs of the sustainable environment and the activity under nanotechnology to save it in any manner, we must be very careful to avoid damage and degradation of the nanotechnology and further harm to the environment. As many of desirable qualities of nanoparticles, such as their high performance results from their high reactivity caused by its delicate surface and microstructure modifications. So, rather to regret in the future for utilizing nanotechnology for saving our ecosystem, we must be aware of all pros and cons related to it. One way which can be archive is utilizing the carbon produced from dumping, managing, and burning of waste. As we know, carbon is the main component of any type of by-products either in form of organic compounds, greenhouse gas, oil spills, etc. therefore utilizing nanotechnology in producing the carbon-based nanomaterials from such by-products of different streams of waste. So, with this concept we can include **3R**'s of sustainable goals i.e., **R**educe, **R**ecycle, **R**euse in the practice by reducing the waste by recycling it through nanotechnology and adding value to it to further reuse it for some related application (Samiha 2013). Thus, generating waste to wealth not helps us to save our planet earth but also provide a less costly approach to trend the technological aspects. Among different forms of carbon, their nanostructures are gripping every field. For example, carbon nanotube (CNT) adsorbents for heavy metals, polar, and non-polar organic compounds and oils thus are commonly utilized for the removal of heavy metal waste from the environment, for sensors, etc. (Musameh et al. 2011). The activated carbon (AC) is already used as a good pollutant absorbent, there used in the medical, environmental, and cosmetic applications (Foo and Hameed 2011), however, nanoporous structure of AC is now day's used for energy storage applications like in supercapacitors (Shi et al. 2014). Other important carbon nanostructures are fullerene and quantum dots used in numerous applications like photo-catalytic, photovoltaic applications, etc. (Martin 2017) the graphene (G), reduced graphene oxide (RGO) and graphene oxides (GO) can be easily produced from specific pyrolysis process of recycling waste plastic, agricultural waste, waste tyre and have used in a variety of sustainable developments based applications i.e., energy storage, environmental cleaning agents, etc. (Pandey et al. 2021).

6.1. Activated Carbon from Waste

Activated carbon, also called activated charcoal (Shown in Figure 4), is a form of carbon processed to have small, low-volume pores that increase the surface area available for adsorption or chemical reactions. Activated carbon is produced using activation processes (either physical or chemical) at high temperatures. The high specific surface area of activated carbon makes it suitable for those applications where adsorption plays a key role (water and gas purification, energy storage). Every organic material after activation gives us activated carbon. Therefore, lots of efforts have been done to fabricate AC from the different treatments of various types of waste. Activated carbon fibre has been prepared from waste cotton gloves by following the activation process which resulted in a highly porous network and used for energy storage application (Wei et al. 2017). Different agricultural wastes (walnut, almond, pistachio) are adopted to convert them into activated nano carbons using physical activation (Nazem et al. 2020). Activated carbon produced from Cork and paper has been used as an adsorbent for methylene blue (Novais et al. 2018). The cellulosic waste from the paper and textile industry is also used to synthesize nano-carbons using the thermo-chemical methods and employed for water disinfection application (Sophia et al. 2016). Nano carbons are also obtained from waste coffee grounds under microwave irradiation (Zein et al. 2017).

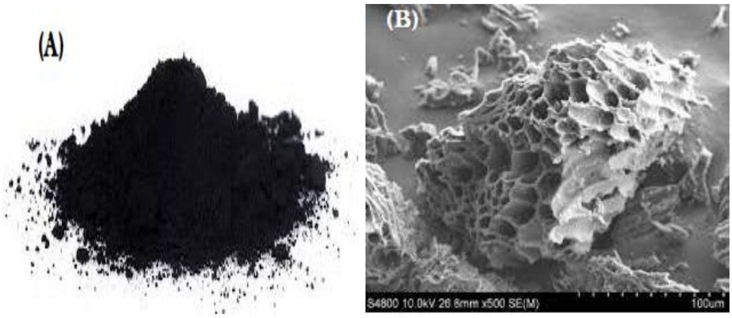

Figure 4. (A) Activated carbon and (B) SEM image of AC depicting porous structure (Rajbhandari et al. 2011).

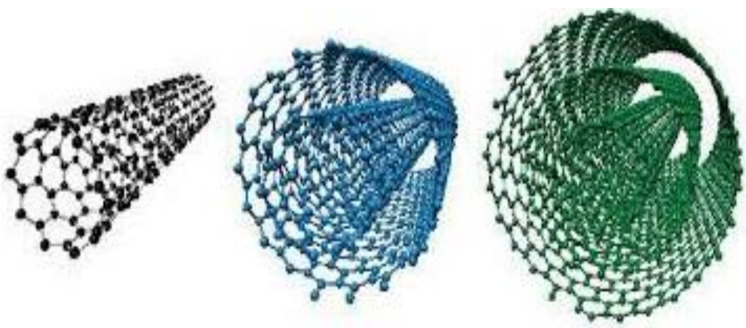

Figure 5. Structure of carbon nanotubes (CNTs).

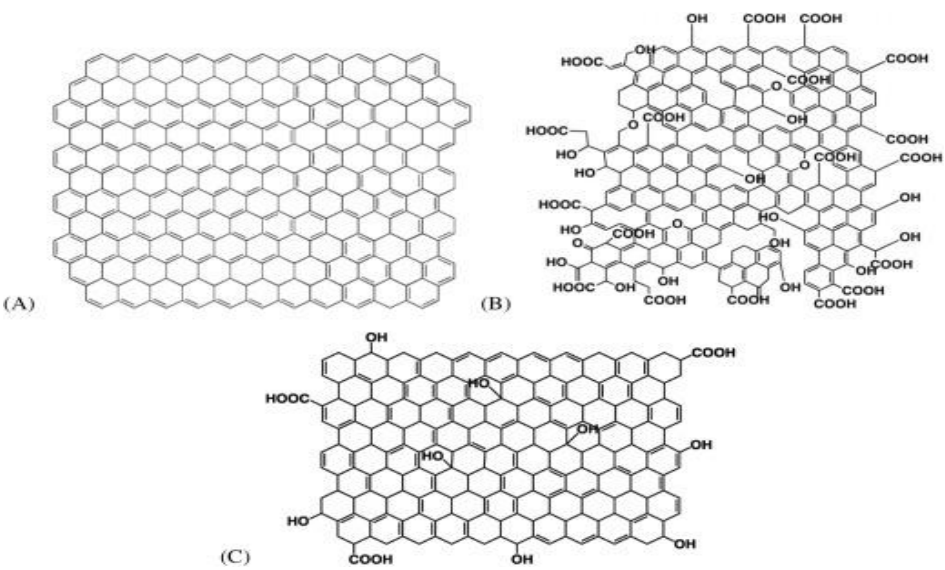

Figure 6. Representative of Chemical Structure of (A) Graphene, (B) Graphene Oxide (GO) and (C) Reduced Graphene Oxide (RGO) (Kumar and Pattammattel 2017).

6.2. Carbon Nanotubes (CNTs) from Waste

CNTs are a cylindrical nanostructure of carbon and can be single and multiwall as shown in Figure 5. They exhibit high specific surface area and are characterized by highly assessable adsorption sites. Their adjustable surface chemistry due to their tubular structure and the capability for surface fictionalization enhance their sorption capacity. As a result, they are mainly act as Carbon nano-tubes The regeneration and the reuse of carbon nano-tubes is their main advantage compared with other nanomaterials and obviously towards other conventional carbonaceous products (Popov 2004; Dresselhaus et al. 1995).

Many researchers have provided different ways of generating CNTs from various types of waste and utilizing them for different applications. Pol and Thiyagarajan (2010) used plastic waste to produce carbon nanotubes via thermal dissociation. Mishra et al. (2012) used waste polypropylene to synthesize carbon nanotubes via single-stage chemical vapor deposition under argon and hydrogen atmosphere. Panahi et al. (2019) used waste plastics for the synthesis of carbon nanotubes with different types of stainless steel catalysts via high temperature pyrolysis. Borsodi et al. (2016) used gaseous products produced from the pyrrolysis of waste plastics to form carbon nanotubes via chemical vapor deposition. Osman et al. (2019) used potato peel waste to synthesize activated carbon via activation process and then this activated carbon was utilized to form hydrophilic carbon nanotubes with the help of nitrogen and iron sources. Suriani et al. (2013) used waste chicken fat to synthesize vertically aligned carbon nanotubes using high-temperature chemical vapor deposition furnace. Quan et al. (2010) has used waste PCBs to form carbon nanotubes via the polymerization process.

6.3. Graphene from Waste

Graphene is one of the novel discoveries in material science which attracts all fields of science and technology. The structure of graphene is shown in Figure 6(A), its unique properties make cab be exploited in various applications. An ideal sheet of graphene is perfectly flat and consists of only trigonally bonded sp^2 carbon atoms. It was the discovery in 2004 by Andre Geim and Konstantin Novoselov at the University of Manchester (Novoselov et al. 2004), who was awarded the Nobel Prize in Physics in 2010. Although lots of methods are available to fabricate graphene monolayer like CVD, Electrochemical, Chemical exfoliation, etc. it would be more novel to utilize the waste for generation of graphene from different types of waste, many efforts have been proposed successfully and utilized the so produced graphene for different applications. Ruan et al. (2011) has used different raw carbon-containing materials such as grass, plastics, roaches, dog feces to grow monolayer graphene on Cu foil via high-temperature thermal treatment. Roy et al. (2016) utilize graphite electrodes from waste dry batteries and after acid cleaning, obtained graphite was used to form graphene oxide which was then reduced using hydrazine hydrate. Singu et al. (2018) made graphene using waste papers via carbonization process and was utilized for supercapacitive application which gave the excellent electrochemical performance. Graphene crystals were made by Sharma et al. (2014) using waste plastic as a precursor via chemical vapour deposition whereas pyrolysis method was adopted by Pandey et al. (2019) for the waste plastic precursor. Udhaya et al. (2018) synthesized graphene using waste mosquito repellent graphite rods with the help of the electrochemical exfoliation method. The flash joule heating method was adopted by Advincula et al. (2021) to convert rubber waste into graphene. This method resolves the problem of conventional time-consuming methods and energetic demand. Wang et al. (2019) adopted the pyrolysis method for directly converting waste tyres into 3D graphene.

6.4. Reduced Graphene Oxide (RGO) from Waste

Other than graphene, there is another derivative of carbon, the graphene oxide (GO) which includes various functional groups attached within it. The chemical structure of GO is represented in Figure 6(B) for better visualization of the various functional groups attached within it. By different methods of surface modification, one can prepare reduced graphene oxide (RGO), which mainly involves by reduction of GO using different reducing reagents and conditions. After reduction, the oxygen-containing groups are removed and the sp^2-hybridized network of the graphitic lattice is recovered, Figure 6(C) represents the chemical structure of RGO. However, it is very difficult to remove all function groups attached with GO to produced pure Graphene. The original method of synthesizing Graphene oxide includes oxidation using $KMnO_4$, $NaNO_3$ in sulphuric acid and nitric acid environment which leads to the production of toxic gases, therefore; single-step oxidation process was adopted by Somanathan et al. (2015) using sugarcane bagasse. Hashmi et al. (2020) has used the orange peel, rice bran to produce graphene oxide. Tea waste is also utilized for the production of graphene oxide. Graphene oxide quantum dots are also derived by using cellulose as a precursor by Adolfsson et al. (2015) following the hydrothermal method. Graphene oxide is also extracted from the graphite waste from diamond synthesizing industries (Ding et al. 2019). 2D graphene oxide is also extracted from 3D waste graphite electrodes in dead batteries using the modified Hummer's method which removes all the contaminants on the external surface of graphite electrodes (Yu et al. 2021). Yadav et al. (2020) investigated waste coir fibre to synthesize graphene oxide and achieved a tremendous high surface area (1117 m^2/g) which was then studied for energy storage application.

CONCLUSION

The world is facing serious environmental challenges related to waste generation, collection, transportation, and treatment. With the increasing population, the volume of the generated waste is also growing day by day which affects both public and the environment badly. Therefore, finding solutions associated with waste management is a priority. The use of nanotechnology is emerging out as a potential solution for most of the problems related to the environment and waste management. Nanotechnology includes those technologies which execute at nanometer scale for various applications. Nanotechnology innovative materials possess very high surface area which increases the reactivity of the material and change in physical properties also. The increased surface area of nanoparticles makes the adsorption process be the highly suited process which can be used in water purification, gas purification, sensing application, energy storage application. Different waste materials have been used as an initial feedstock for synthesizing nanomaterials. Researchers have adopted different methods and materials to get value-added products from wastes. However, we must be aware of all pros and cons related to the use of nanotechnology in waste management. As the main issue of dumping, managing, and burning of waste are the generation of carbon as it is the main component of any type of by-products either in form of the organic compounds, greenhouse gas, oil spills, etc. Therefore, utilizing nanotechnology in producing the carbon-based nanomaterials from such by-products of different stream of waste would be the key solution towards sustainable development. So, with this concept, we can include **3R**'s to produced carbon for sustainable goals i.e., **R**educe, **R**ecycle, **R**euse practice by reducing the waste by recycling it through nanotechnology and adding value to it for further reuse in some related applications like energy, sensing, power generation, etc.

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Chapter 4

ADVANCEMENT TOWARDS SUSTAINABLE MANAGEMENT AND UTILISATION OF AGRICULTURE WASTES IN THE GLOBAL ECONOMY

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ABSTRACT

In the global economy, agriculture is the chief contributor in terms of biomass production. At present, recycling and reprocessing of agriculture wastes for bio-fuel and energy production has become a gradually significant development area, having greater prospective. India is an agro-based economy which generates about 400 million tonnes of agriculture/forest wastes. The technologies for successful conversion of agricultural wastes provide a new venture for production of augmented products such as feed, fodder, food, organic/bio-products and bio-fuel/energy. Ball milling and chemical activation techniques are used for conversion of wastes like coconut husk, cocoa pod, calabash and palm midrib for producing activated carbons. Such activated carbons are used in superconductors and batteries. Processes like pyrolysis liquefaction, gasification, combustion, and fermentation, has been used for conversion of agro-wastes into heat, electricity, fuels, ethanol and methanol respectively. Circular economy approach could be used for producing value added products by processing agro-wastes into bio-plastics, bio-energy, bio-fertilizer and bio-chemicals. For instance, succinic acid and glucose are produced from food/agro-wastes via fermentation. Bio-refinery systems are used for recycling rice husks for producing synthetic lubricants. Molding, pulping and hydro-separation methods are used for production of sound proof systems, absorbent materials, thermal insulators and packaging materials by recycling sugarcane bagasse, kenaf fibers

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etc. In recent years, research focused on utilization and management of agricultural wastes has led to improving and providing healthy environment by reducing resource exploitation, climate management and providing social and economic benefits.In long term, the refinement in agro-waste management systems could provide new insight in the development of novel advantageous materials of industrial importance including people from rural areas, research institutes on a cost-allocation basis consequently leading to a sustainable growth. This chapter provides different aspects being carried out in the field of agriculture waste management.

1. INTRODUCTION

In the 20th century, traditional agriculture production system has been completely overtaken by advanced agricultural technologies leading to intensification of agricultural production by the use of concentrates, pesticides, mineral fertilizers and herbicides. These systems led to an increase in the agricultural yield with change in composition and quality of production. In the past 50 years, the production has increased three-fold due to soil/land expansion, green revolution and increasing population (FAO, 2017a; FAO and OECD, 2019). Per day about 23.7 million tons of food is produced by agriculture across the globe (FAO, 2017a). Large production generates huge amount of agricultural wastes. The valuable agro-wastes generated could be recycled and reused for multiple purposes such as fuel and energy production, bio-fertilizers and bio-chemical production. Proper usage and management of agro-waste is very essential because if not managed or regulated they may cause environmental hazards affecting animal and human health. The over production has created a huge environmental pressure having negative impact on air, soil and water resources (FAO, 2017b), eventually compromising human health (Bos and Hamelinck 2014). About 21% of greenhouse gases are generated through agriculture wastes (FAO, 2016). Most of the agro-based wastes are disposed either through random land filling, burning or dumping. The burning causes release of different greenhouse gases contributing to climate change and global warming (Bos and Hamelinck 2014). These issues have now created a serious concern for introducing an alternative-way for production of renewable energy resources (Okonko et al. 2009).

One of the aspect of global waste management strategies is maintenance and management of agro-wastes for industrial purposes to meet human needs and manage environmental pollution. In the concept of bioeconomy, agriculture contributes the largest sector with maximum biomass production (Bracco et al. 2018; European Commission, 2012). This provides great prospect for development of green markets, providing new jobs/work to people by involving manpower in generating value-added products such as bioenergy, fodder, bio-fuel and food by conversion of different forms of agricultural wastes (Table 1) (EC, 2017; EU, 2013; Scarlat et al. 2015; Mohanty et al. 2002). The strategies of Common Agricultural Policy (CAP) have adopted the policy for prioritizing and promoting circular bio-economy by providing financial support and sensitizing farmers for proper management of agriculture wastes and as in price control of biomass resources (EC, 2017a, 2019).

Table 1. Agricultural wastes processing into value-added products (UNEP 2009)

Agriculture element	Waste	Process	Main Product	References
Wood	Construction waste woodchips, lumber fromThinning	Direct Combustion	Electricity	(UNEP 2009)
Palm, Coconut, rice, sugarcane, wood	Bagasse, rubber wood, palm nut shells, husks, coconut shells and wood residues	Gasification	Electricity	(UNEP 2009)
Wood, crops	Wood, animal manures,crop waste	Gasification	Electricity	(UNEP 2009)
Corn, barley, wheat, rice, sorghum, and cotton	Straw and stalks	Gasification	Pure H_2, CO_2, SO_2, electricity	(UNEP 2009)
Corn and rice	Rice straw, corn cobs and husk	Gasification	Steam, Syngas for electricity	(UNEP 2009)
Rice, coffee, corn,	Rice Hull and other farm by-products such as coffee hulls andcorncobs	Combustion	Heat	(UNEP 2009)
Rice, coffee, coconut, corn	Rice hull, peanut, corncobs, coconut husk, wood chips, shells of pili, and coffee bean	Pyrolysis	Carbon producing power and combustible gas	(UNEP 2009)
Wood	Dry sawdust	Combustion	Steam	(UNEP 2009)
Coconut	Charcoal and coconut shell	Combustion	Heat for drying	(UNEP 2009)
Sugarcane, corn, and wood	Feedstocks from renewable waste materialsincluding organic waste, wood waste, corn stover,bagasse, sewage, digester gas orlandfill gas and manure	Syntec process	Bio alcohols and ethanol	(UNEP 2009)
Palm, Coconut, rice, sugarcane, wood	Bagasse, rubber wood, palm nut shells, husks, coconut shells and wood residues	Thermal conversion Process	Fertilizer, renewable diesel, and special chemicals	(UNEP 2009)
Corn, rice, pineapple, citrus, sugarcane, wheat	Corn cobs, wheat, pineapple plants, sugar cane, citrus pumice, rice husks, fruit drops	Reduction	Additives for beverages,Ethanol, industrial absorbents and animal feed	(UNEP 2009)
Sugarcane, rice	Sugarcane Waste and Rice Hulls	Tilby process	Woody Fibers in the form of lumber materials	(UNEP 2009)
Wheat, oil palm fruit	Wheat and oil palm fruit residue	Recycling	Biodegradable packaging materials	(UNEP 2009)
All types of biomass materials	Biomass waste	Densification	Honeycomb briquettes	(UNEP 2009)
Tobacco, coconut, corn, wood, sugarcane,	Fiber, wood residue, sugarcane, bagasse, tobacco, coconut coir and corn stalks	Densification	Panel board	(UNEP 2009)
Kenaf, Sugarcane	Kenaf pulp and Bagasse	Hot melt process	Packaging and Paper materials	(UNEP 2009)
Abaca	Abaca leaves	Tuxying	Abaca leaf sheath and fibres	(UNEP 2009)
Abaca	Fiber	Decortication	Yarnand Ropes and other products	(UNEP 2009)

Table 1. (Continued)

Agriculture element	Waste	Process	Main Product	References
Agricultural products	Agricultural waste	Thermo Chemical Process	Cellulosic ethanol	(UNEP 2009)
Agricultural Products	Agri-waste	Carbonization	Synthesis gas and carbon-rich end materials	(UNEP 2009)
Corn, sugarcane	Corn stover Bagasse	Fermentation	Fructose, xylitol, cellulose, sorbitol, lignin and unbleached	(UNEP 2009)
Woodrice, peanut, corn, coffee, pili, coconut	Rice hull, peanut, corncobs, coconut,hull, wood chips, shells of pili and coffee bean	Pyrolysis	Gas	(UNEP 2009)
Sorghum	Straw and Leaves	Biological Conversion	H_2 and CO_2 Biofuels (Ethanol and Hydrogen)	(UNEP 2009)
Rice	Rice hull and straw	Fermentation	Ethanol and silica/sodium oxide and lignin	(UNEP 2009)
Eucalyptus, Pongamia, Sababul, neem, coconut,fronds	Crop residues	Gasification	Producer gas	(UNEP 2009)
Wood	Wood chips, fuel wood, briquettes and twigs	Combustion	Heat for drying	(UNEP 2009)
Cotton, sugarcane, wood, kenaf, and soybeans	Chicken litter, cotton stalks, wood chips,forestry residues, soybean plant residues, kenaf, sugarcane andbagasse	Combustion	Heat	(UNEP 2009)
Olives	Waste products from the olive oil processing	Incineration	Electricity	(UNEP 2009)

2. Types of Agriculture Wastes

Agriculture wastes are categorised into two major kinds of waste. First, waste generated from agricultural products and by products. Second, residual wastes generated from agricultural activities. The first category includes biomass wastes generated from organic wastes, animal corpses, dejections of animals, animal manure and secondary crop production. The second category includes organic wastes generated by wood and paper residues, rubber, plastics, pesticides, petrochemical wastes and inorganic wastes from inorganic pesticides, wastes from tools, scraps, and agriculture machines, also including pharmaceutical wastes (Seadi and Holm-Nielsen 2004).

The agro-industrial wastes are also divided into field and process residues. Third category includes industrial residues produced by processing of agricultural products (Figure 1). The field residues include the remains left in the field after harvesting of various crops. These residues include stems, leaves, pods, seeds, stalks etc. The processed residues include shell, husks, straw, pulp, molasses, stubble, leaves, roots, bagasse, stem and peel. These processed residues and field residues are mostly underutilized. With proper and controlled management these field and process residues could be used for soil quality improvement, manufacturing fertilizers/manure, controlling soil erosion, animal forage and many other processes (Seadi and Holm-Nielsen 2004; Sadh et al. 2018).

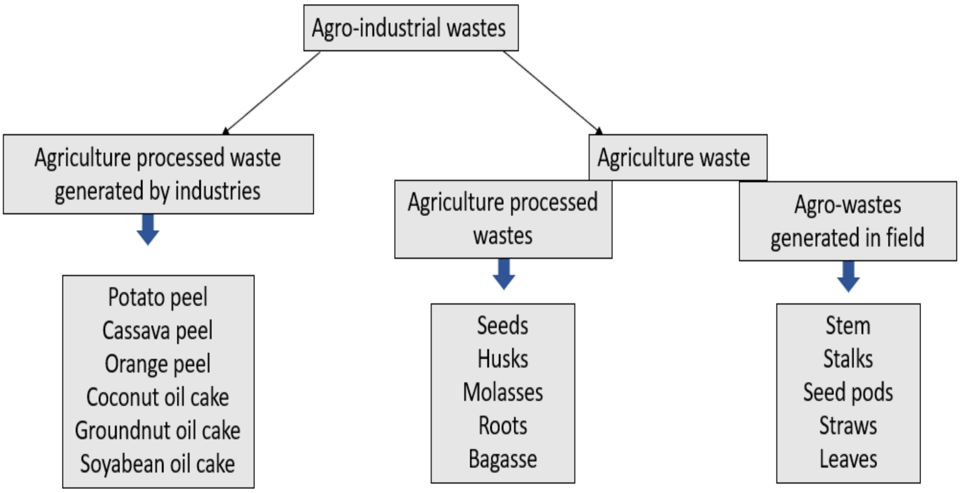

Figure 1.Types of agro-industrial wastes.

The food processing industries including those involved in production of chips, confectionary, juices/fruit juices etc. produce a large amount of organic effluents every year. The wastes produced by these industries include potato peels, oranges and other fruits peels, coconut husks, coconut, groundnut, soybean oil cakes, which are rich in ash, lignin, cellulose, carbon, hemicellulose, nitrogen etc. These wastes if processed properly, have the potential to produce bio-fuels such as bio-ethanol, bio-gas etc. (Sadh et al. 2018).

3. Environmental Hazards of Agricultural Waste

There is tremendous pressure to increase agricultural activities to provide food for the ever-increasing population. This initiated diversification in crop and livestock production like rice, cassava, poultry, cattle, maize pigs and so on, as well as the handing out of these products into garri, sausages, flour, chicken, pork, beef, cheese, butter and among others. Due to these agricultural activities waste generation in the form of dung, straw, manure, urine, slurry, blood, shells and other products which degrades the environment. Agricultural wastes like sludge ruin the environment and unbalanced it. A lot of health concerns are related to environmental pollution which includes cholera, headache, dysentery, malaria, diarrhoea, catarrh and among others. Agriculture waste also causes soil erosion and sedimentation. Tilled fields with increasing erosion rates can cause unnecessary deposition of fine sediments in receiving streams that can block interstitial spaces and river-bed gravels which are vital spawning habitats for various fish species. Moreover, suspended sediments can decrease light penetration, scour surfaces and may obstruct in respiration, drift rates and feeding mechanisms of macro invertebrates and fish (Doeg and Koehn 1994; Wood and Armitage 1997; Relyea etal. 2000).Use of different pesticides for the removal of harmful insects, microorganisms and other pests when they get mixed with soil, food, water and air can cause problems on the agricultural foods that may affect human health and therefore become an environmental problem. It is a well-known fact that pesticide runoff is a major contributor to the surface-water contamination (Wohlfahrt etal. 2010). Furthermore fields, ground water, lakes, streams and sea are going to be converted into a kind of toxin storage in future (Önder etal. 2011).There are various instances of environmental pollution leading to serious epidemics of human diseases (Kolpakova 2004; Deleanu etal. 1981). In agricultural areas, microbes, toxic heavy metals, like lead, cadmium, arsenic, fluorides and various toxic agrochemicals contaminates the water (Wittmer etal. 2010, Belden etal. 2000 and Meyer etal. 2011). According to Gadde etal, open burning of crop stubble generates harmful chemicals such as polychlorinated dibenzo-p-dioxins, polycyclic aromatic hydrocarbons (PAH's) and polychlorinated dibenzofurans (PCDFs) (Gadde et al. 2009). It is found that inhaling of minute particulate matter of less than PM 2.5 μg causes asthma and can even exacerbate symptoms of bronchial attack (Kumar etal. 2015). Similarly, industry farming contaminates the world with industrial processes that increases substantial quantities of animals (usually cows, pigs, chickens or turkeys) in congested, restrained and unsanitary conditions (Hatz 2009).The oldest and most well-known agricultural respiratory syndrome are from exposures to agricultural dusts like grain processing and confined animal feeding operations (CAFOs), e.g., swine confinement facilities (Kirkhorn and Facoem 2001). Organic dust toxic syndrome (ODTS) is very common and can be observed in near about 34% of CAFO workers (Von Essen and Donham 1999).

4. Agricultural Waste Management System (AWMS)

Governments from different countries have made an initiative to manage agricultural waste biomass and produce value-added products or bio-resources. But still many efforts are required to be done to fill the major gaps due to "set aside or imperceptible' events involved in agricultural waste management (UNEP 2009). There is a need to sensitize people and create awareness among them to utilize the waste to convert into energy resources and useful materials. This reutilization of wastes would not only reduce the waste disposal costs but also create an income from the trading of products generated after recycling of the wastes. For raising awareness among people, UNEP (United Nations Environment Program) has started an ISWM program.

ISWM is Integrated Solid Waste Management program which is based on reducing, reusing and recycling of solid wastes (UNEP 2009). This program includes management of all types of waste streams involving isolation, assortment, transportation, recycling, energy or product recovery and final discarding. It has been found that proper separation/categorization and recycling of wastes could significantly reduce unwanted dumping of wastes into landfills and convert them into useful resources. Development of an ISWM program needs research and exclusive data on the current waste situations with appropriate financial support. It requires helpful strategy and outline to develop large systems that are furnished with eco-friendly technologies and instruments required for reusability, recyclability and productivity of value-added products from solid waste (UNEP 2009).

The current emerging area of concern for the policy makers has been the agricultural waste management (AWM) for sustainable development and ecological agriculture (Hai and Tuyet 2010). Dispensing agricultural waste into the environment either with or without treatment has been the naive and wonted process for agricultural waste management (Obi et al. 2016). In order to put transmission of hazardous materials and contamination of water, land and air to a halt, there is a necessity to contemplate dregs as a promising asset rather than infelicitous and undesirable. This entails change in people's convictions and perspective, better methodology for agricultural waste treatment and employing cutting edge technology (Obi et al. 2016).

The uncontainable decomposition of organic waste primarily manure obtained from animals gives off an odour due to gases, in worst case it can also trigger acid rain due to ammonia volatilization (Wright 1998). Quality of air, water and soil deteriorates when waste is stagnant or when it is left untreated making it cradle for insects and flies and a hub for diseases. By the dint of aggravation of animal production in a confined space, a concern about the following arises:

- Escalated levels of phosphorous loadings and nitrogen and its effect on water quality
- Content of antimicrobial compounds and pathogens in manure.
- Emission of malodorous gases like ammonia, nitrous oxide and methane
- Phosphorous loading and Potassium affecting the soil quality (Fabian et al. 1993).

To maintain and inflate the quality of water, soil, air, animal and plant resources, AWMS which stands for Agricultural Waste Management System is used. In AWMS vital constituents are established, governed to check and wield agricultural product's derivative to serve the aforementioned purposes (USDA 2012).

The system is outlined to serve agricultural debris of all kinds over the year using what is known as total systems approach. Which kind of processing would be applied to deal with agricultural waste is determined by its paricultar trait called Total Solid concentration? (USDA 2012). Several factors that play the key role in altering TS concentration are how hydrated the animal is, variety of animal, quality and kind of animal feed.The TS concentration can be regulated; it can be minimized by adding water, on the other hand it can be increased by adding waste and beddings to the debris. The volume of the waste to be handled is correlated to the TS concentration (Obi et al. 2016).

The initial outlay of solid waste system can be superior to liquid management. Moreover, solid waste management systems are comparatively tougher to administer and automatise. AWMS comprises of six basic rudimentary steps namely collection, production, storage, transfer, treatment and utilization. Collection is capturing and accumulating debris from the site of dumping or genesis (Hai and Tuyet 2010). AWMS objectives must target on spotting the site of collection, procedure carried out for collection, drudgery needs, collection scheduling, administration and establishment expenses, structural amenity and requisite tools etc. (Figure 2) Production is correlated to the characteristic and quantity of the waste generated. When quantity of the waste generated becomes sufficient then the need to manage becomes a concern. The audit of waste consists of analysing the consistency, its type, timing and location of the scrap generated (Obi et al. 2016). The role of storage relates to momentary confinement or retention of the debris. The waste management storage facility issues command over the timing and scheduling functions, usage of waste and its treatment for instance. This may be influenced by climate or operations interfering in it (USDA 2012).

There are numerous issues in the waste management system which must be recognized and addressed, like: computation of the size of storage, identifying type of storage and effect on density of waste due to the type of storage, cost of installation, cost of regulation and management. Techniques outlined to get rid of the noxious characteristics of debris and effluent by chemical, biological and physical means is referred as treatment of waste (Obi et al. 2016). Prior to treatment, some perusal needs to be done like choosing location, category of treatment, approximating size and cost of inducting treatment service. Transfer refers to passage of waste around the system either as muck, solid or liquid from accumulation to usage phase. Stimulating debris for benign usage is referred to as utilization. It encompasses requiting non reusable scrap back to environment and reprocessing the reusable wastes (USDA 2012).

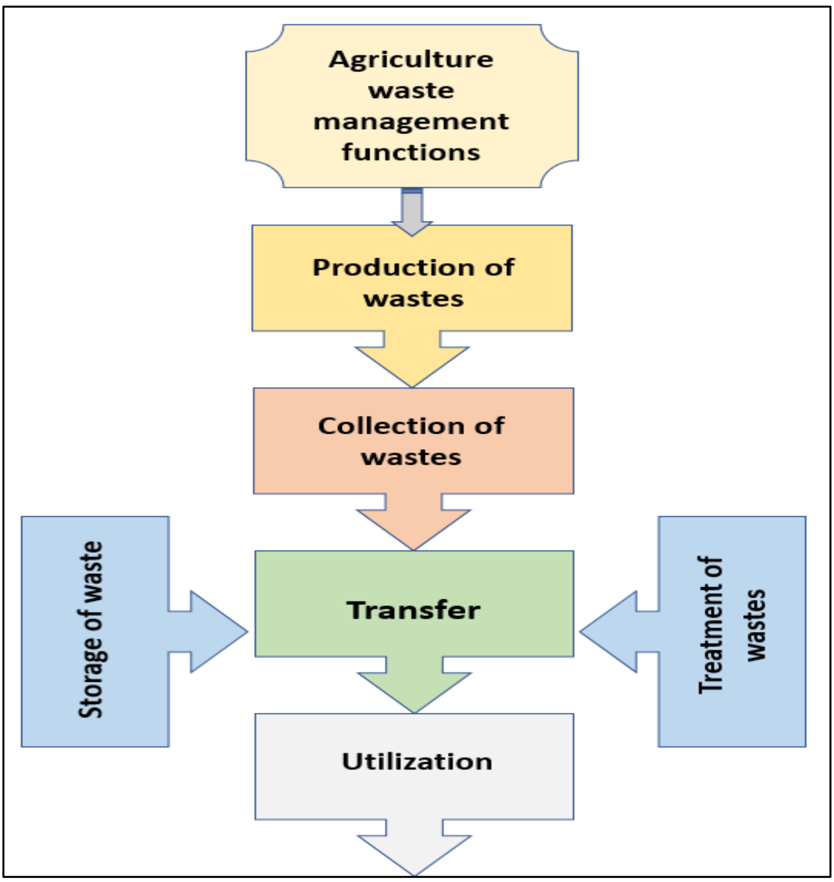

Figure 2. Agriculture waste management system functions (AWMS).

4.1. AWM Including the '3R' Approach

The idea of reducing waste lowers the negative impacts of production of waste and its volume by employing uncomplicated procedures for reusing scrap material and by producing same or revised product using the recycled waste. This is renowned as ‘3R’ approach. Using 3Rs for waste management prevents consumption of new resource as waste material and is used as input to create similar or modified version of the same commodity. Using 3Rs add worth to already used up resource (USDA 2012; Obi et al. 2016; Hai and Tuyet 2010). The fundamental idea behind 3Rs focuses on accomplishing significant reduction in waste production by:

- Watchful use of commodities to cut down waste generation.
- Reusing items or its components if there is even a slim chance of reusing it.
- Reusing waste afresh

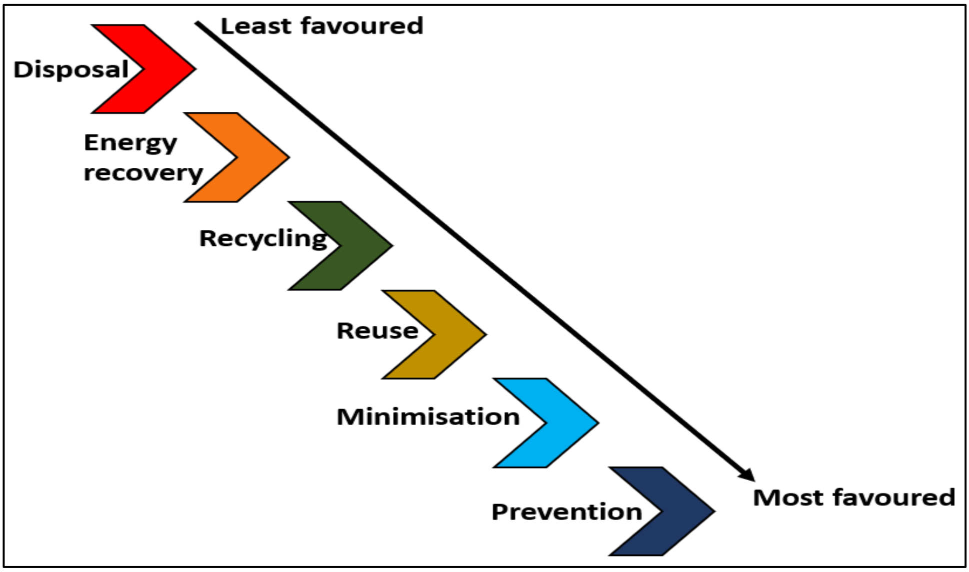

Figure 3. AWM involving 3R Hierarchy.

4.2. The AWM Involving 3R Hierarchy

In order to cut down the amount of waste produced and to maximize the possible gain by the product. A waste management hierarchy is followed which is 3Rs.The 3Rs is an acronym for Reuse, Reduce and Recycle (Obi et al. 2016) (Figure 3). The 3Rs comply with a hierarchical sequence. Although, the hierarchy has stayed fickle over the last few decades but its essence has remained the same. The 3Rs is typically demonstrated using a hierarchy pyramid, the environmental gains associated with a particular approach is stacked on top of each other from bottom to top in the pyramid (USDA 2012).

Although in various applications, some agricultural residues have been given precedence, it is considered that surpluses normally occur and the wastes can be transformed into solid-fuel briquettes. On the basis of demands these technologies can be evolved. In contemporary situations it is possible to choose three recycling techniques for agricultural debris to be the most appropriate for emerging groups. These are fodder for animal, energy produced by combustion of briquette waste logs or biogas and composting for land repossession and improvement. There are several other methods, such as fiber boards, gasification, silicon carbide, chemicals, pyrolysis, etc., that could be ideal for different countries as appropriate.

5. Utilization of Agricultural Wastes

A favourable climatic condition not only favours crop cultivation, instead also promote growth of weeds and unwanted crop insects. This condition demands use of weedicide and pesticides for protection of crops from insects and weeds. Farmers overuse these chemicals and throw the containers/bottles into barren lands or ponds causing environmental pollution (Obi et al. 2016). The Plant Protection Department (PPD) estimated that about 1.8% of weedicide or pesticide chemicals remain in the containers which leach out contaminating the agricultural land (Dien et al. 2006). The chemicals enter and accumulate into the crop through water uptake, affecting the quality of production resulting in food poisoning. Overuse of fertilizers by farmers for increasing crop production results in the accumulation of excess of fertilizers into the soil contaminating the ground water while, another portion of chemicals leach out and enters into the ponds, lakes/rivers contaminating the water (Obi et al. 2016; Dien et al. 2006).Excessive usage of manure, fertilizers result into accumulation of heavy metals which leach out or combine with agricultural wastes. The presence of heavy metals in agricultural wastes may result from human activities such as consumer products leftovers, metabolic wastes and water pipes corrosion. Also, waste sludge's and industrial wastes release metals in waste water streams. These factors cause contamination of surface water with hefty loads of heavy metals (Connell and Miller1984).

6. Waste Utilization Routes

Based on the requirements, various recycling technologies have been introduced. In actual it is possible to choose three agricultural waste recycling techniques to be the most appropriate for emerging societies (Figure 4).These are solid animal fodder, fuel production through briquetting or biogas production and land reclamation composting. There are several other techniques that may be appropriate for various nations according to their needs, for instance, chemicals, silicon carbide, gasification, pyrolysis, fiber-board, etc., as they need to be processed mechanically and chemically to make them edible for direct consumption by animals. The implementation can also rely on the locality of region and kind of financial activity. The content of organic matter appears to offer priority over its utilization as fuel to the usage of agricultural waste as fertilizer and as animal fodder, respectively. Other constituents, such as the content of lignin, hemicelluloses and cellulose gets entitled as agricultural remnant for the manufacture of enzymes, resins and chemicals (Khedari et al. 2003).For instance, Lange and Ojewole(El-Haggar 2007) replaced (up to 30 percent) maize offal and maize with cowpea hull and remnant in chicken feed. Fibre residue and roughage require supplements to reinforce them as they are usually poor in nutritional content. This lowered the cost of feed (due to rising price of maize) and also increased the yield (egg weight). It was found by a study based on an experiment which involved feeding *Tilapia* fish (Otubusin, 2001) with a blend of agro-industrial residue- rice bran, corn bran, and brewers waste. The ratio of 1:1 (corn: bran: rice) gave the best result as far as specific growth rate, best fish weight and best feed conversion ratio were concerned.

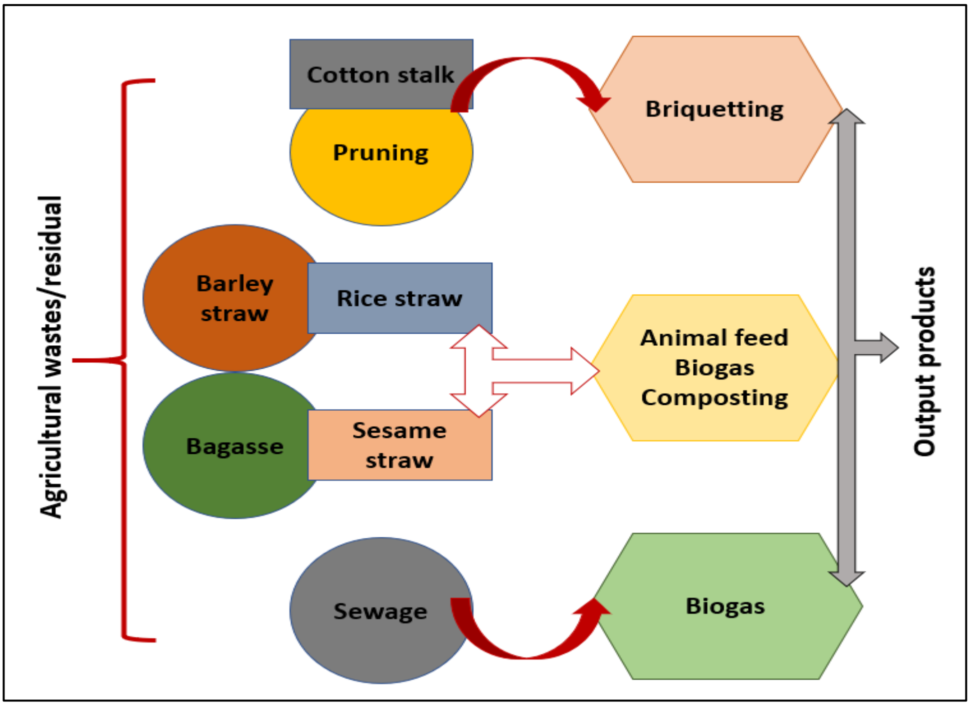

Figure 4. Three agricultural waste recycling techniques, biogas production, composting/animal fodder and briquetting.

6.1. Briquetting

Agriculture wastes including wood wastes, burn quickly producing fuel having very less energy value per volume which makes the wastes unproductive. Various techniques for proper utilization and management of agriculture residues are being pursued which involves compaction of the wastes into briquettes or pellets. The process involves reduction of the size by hard pressing the waste. These fuel briquettes solid logs are easy to store and transport and could be used in industries and home. The major advantage of using briquettes waste blocks is that the combustion process could be controlled and a steady fire state could be maintained. Thus, the briquette waste logs could be directly used as fuel unlike the coal or fuel wood used in ovens and stoves. Countries like Africa, India and Thailand etc are using fuel briquettes as a substitute of coal and fuel wood to reduce the disposal of agricultural and farm-waste (Bhattacharya et al. 1989).

The process of briquetting improves the property of materials by improving the volumetric value and makes it accessible for diverse applications including industrial and domestic applications. The process of briquetting is applicable for a wide range of materials including not only agricultural wastes but also involving agro-industrial wastes such as rubber, plastic and other combustible materials that can be converted into waste blocks/pellets using heavy press machines (El-Haggar 2007).

6.2. Animal Fodder

In developing countries, efforts are being made for developing animal feeds having optimal content of required proteins, starch, fiber and fat. Crop residues that are rich in fibre are supplemented with protein rich grains and forage to domesticated animals (Leng et al. 1992).

The shortage of animal food in developing countries contributes to the importation of raw materials and consequently high prices and a decline in the production of livestock. It will help a lot to resolve this deficiency by converting some of these wastes into animal food stuffs. Such wastes are highly fibrous making them hard to digest (El-Haggar 2007). In their natural form, the size of the waste may be too large or tough for the animals to consume.

Several methods have been used to solve these two problems to turn agricultural and food processing wastes into a further consumable form with an advanced wholesome goodness and better digestibility. To transmute the roughage (waste) into an edible form, chemical and physical/mechanical treatment methods have been used. The incorporation of supplements can augment goodness in the products. Grinding, slicing, dampening, shredding, water soaking and steaming under pressure are included within the mechanical treatment process (El-Haggar 2007).

The mechanical technique has shown decent outcomes by improving animal digestion, but they have never been prevalent due to high expenses thus making it unviable for small farmers. The method of chemical treatment involves use of ammonia or urea which is more practical as compared to mechanical method of treatment. By adding 2% of urea or ammonia to the total mass of waste, improves the results significantly. It is recommended that the treated and processed waste should be covered with a packaging material, typically made of 2 mm thick polyethylene. The waste after treatment is exposed after 2 weeks in summer and 3 weeks in winter and is left open for 2-3 days before being used as animal feed to release all the remaining ammonia (El-Haggar 2007).

6.3. Biogas Generation

Biogas generation is another application of processed plant leftover or waste residuals. Biogas is a durable energy source. Biogas can be produced via processing or employing certain types of agricultural wastes including rice straw, malt straw, ground cotton stalk, wheat straw and maize stalk.The process of transformation of solid biomass for example, agricultural residues and wood wastes into inflammable gas (typically called producer gas) is called biomass gasification (El-Haggar 2007).

Biogas is a combination of gases, predominantly carbon dioxide and methane, arising from the activity of bacteria through anaerobic fermentation of organic materials.In the presence of finite air, the process involves exposing appropriately dried agricultural wastes or residues to the thermal putrefaction. Biogas is used as a fuel in internal combustion (IC) engines. The Biogas has been found suitable and can offer prospects to industries involved in small-scale power generation to meet the desires of extents that have so far to be linked to the grid.The gas from biomass is anticipated to be 60-70 percent capable of substituting conventional fuels requirement in India.In many developing countries, biogas is yet not much prevalent. In order to determine the potential use for biogas processing, (Thakur and Singh

2000) conducted bench scale research on some agro-wastes and weeds. Banana stem was found to be more apposite in producing about 95 L/kg of total solid (TS) in contrast to cow dung that produced 70 L/kg of total solid waste.Approximately, about 45 days retention period was essential for huge methane output.

Biogas produced using paddy straw, *Partheniumhysterophorus*, bagasse, water hyacinth, wheat straw, *Cannabis sativa* and *Croton sparsiflorus* gave 72-80 L/kg of TS (El-Haggar 2007).Biogas is produced by the anaerobic fermentation under controlled conditions of organic constituents by microorganisms. Biogas is a blend of gases primarily carbon dioxide and methane that results from anaerobic fermentation of biological matter by bacteria. Due to the lack of energy policies, biogas has lower precedence in many developing countries. There are no energy policies in most developing countries to leverage biogas and realize its potential to be a substantial part of the inclusive energy output for the country.In remote regions, massive volumes of organic waste are created, such as municipal solid waste, agricultural debris, municipal treatment plants, organic waste and sludge, as well as deceased animals and animal compost.All of these can be regarded as a biomass, an organic material based on carbon could be an amazing source of fertilizer and biogas (El-Haggar 2007).

6.4. Fertilizers

There are substantial amount of costs and benefits of using animal wastes as fertilizers (Timbers and Downing 1977). The chemical fertilizers are regaled with various minerals like 61%, 19% and 38% of potassium, nitrogen and phosphorus respectively (CAST Report 1975). Adding manure to the soil helps in increasing water retention capacity of soil and maintaining its structural stability. But, on the downside we have adulteration of the ground water due to confinement stored fertilizers, additional expenses of storage, transportation and distribution come along as well. Fertilizers that primarily use manure often cause bad odour (Mokwunye and Bationo 2002). When poultry manure is mingled with mineral phosphorus then the product thus obtained can be used in farms to increase fertility and productivity of the land, as the poultry manure itself is very rich in phosphorus which is vital for crop growth and its nourishment (Obi et al. 2016).

6.5. Composting

The process which involves decomposition of organic matter under controlled conditions by microorganism is known as composting.Composting is done to achieve rich soil by killing pathogens and enhancing the organic debris.Justus von Liebig (Epstein, 2017), a German chemist, discovered in 1876 that northern African lands which supplied two-thirds of the grains to Rome, had become less fertile, losing their efficiency and productivity.It was due to the fact that the waste never returned from North Africa; rather, it was dumped into the Mediterranean. The agricultural wastes produced from rice, maize, cotton crops residual is abundant in organic substances. The soil provides organic substances to the plants, so the soil needs it back to further continue growing good plants.

Organo-mineral fertilizers, a commodity produced out of composted crop and animal leftovers (palm kernel cake, sawdust, cow dung, shear nut cake and poultry manure) and fixed city trash enriched with local minerals verified to be an effective technique for waste management (Ogazi et al. 2000). The degradable city waste decreased the composting period from 84 to 55 days and the usage of cassava/maize intercrop fertilizers escalated the yield of maize by 20% when grown on plot supplied by mineral fertilizer and 60% on plot with zero fertiliser.The yield of cassava has increased by 200% on plot with no fertilizers and 40% on plot supplied by mineral fertilizers.

Composting is the most typical organic waste recycling processes closing the natural loop.Moisture and oxygen are the paramount factors affecting the putrefaction of organic matter by microorganisms. Temperature too is a crucial factor, which is a result of microbial activity. The pH, time, nutrients (carbon and nitrogen) and physical features of the raw substantial are the other miscellaneous variables that affect the composting process (porosity, texture, structure and element size).The decomposition rate and its standard depend on the raw material being picked and mixed.To renew the oxygen supply for the microorganisms, aeration is desired.

The passive composting method (E1-Haggar 2003) is the suggested practice for emerging groups constructed on mechanical and pecuniary factors.Positive aspects of composting are the upgradation of soil structure by affixing the structure of organic matter and pathogens as well as using agricultural wastes that can be the basis of enormous contamination, if charred or burned.Since, compost materials typically consist of some biologically resilient complexes; it may not be possible to achieve comprehensive maturation (stabilisation) through composting. The time needed for stabilisation of the composts relies on different environmental factors within and around the composting mass/heap.In order to calculate the degree of stabilisation, some conventional metrics can be used, such as the absence of odour, reduction in temperature and the lack of insect’s attraction in final goods.The compost can be modified to generate organic fertilizers for organic farming by adding natural rocks such as phosphate (source of phosphorus), dolomite (source of magnesium), feldspar (source of potassium), etc (El-Haggar 2007).

Organic farming leads to healthier taste, has no effect on the health of people and is less detrimental to the climate. Organic farming is aimed at generating good yields, lowering external costs, preserving biodiversity, saving resources and maintaining healthy soil.

6.6. Anaerobic Digestion

Methane gas which is befitting for heating purposes such as water heating, boiler operation and grain drying can be produced from agricultural waste peculiarly manures. The production of methane-rich gas is a dual step process which is renowned as anaerobic digestion. The organic matter (volatile solid) is disintegrated to form organic acid to begin with, which is then followed by its utilization by methanogens to produce or churn out methane-rich gas, consequently the gas formed after this process has the following composition: N_2 0.5-3%; H_2, 1-10% with traces of H_2S; CO_2, 25-45% and methane 50-70%; The heating value of the gas turns out to be 18-25 MJ/m^3 (Timbers and Downing 1977). The monetary stipulation of setting up a digestion plant is fairly high and methane gas by its very nature is volatile.

The aforementioned two points are handful negative aspect of digestion system but the advantages far outbalanced the drawbacks. Digestion system produces sludge by stabilizing wastes from poultry, agricultural, diary wastes. It also eliminates the odour and keeps the fertilizing capability of waste intact (Obi et al. 2016).

6.7. Adsorbents in the Elimination of Heavy Metals

Unlike organic pollutants, heavy metals like zinc, copper, chromium, cadmium, mercury and lead ions are non-biodegradable besides that they can be noxious for various life forms and thus they pose huge threat to the environment (Gupta et al. 2001). Researchers revealed that adsorption using adsorbent like activated carbon has tremendous potential for treatment of waste stream by getting rid of heavy metal ions from it. Over the last few years researchers have deduced that agricultural waste such as rice husk (Ayub et al. 2002), sawdust (Ajmal et al. 1996), sugarcane bagasse (Mohan et al. 2002), coconut husk (Tan et al. 1993), neem bark (Ayub et al. 2001), oil palm shell (Khan et al. 2003), etc can be used as a reasonable substitute for treatment of effluents containing heavy metals through the adsorption process.

6.8. Pyrolysis

Pyrolysis is a superior methodology to employ agricultural waste in contrast to hydrolysis and hydro-gasification. In pyrolysis system, agricultural waste is made to scorch in a temperature range of 400-600°C without oxygen which leaves behind char and vaporizes a portion of material. This technology helps in replenishing energy and yield chemicals, oils, low heating value gas and char. Agriculture has remained as the area of interest for many due to its numerous applications like glucose as a source of carbohydrate, fertilizers containing ammonia and ethanol as fuel (Obi et al. 2016).

7. Waste To Energy Conversion

7.1. Electricity Generation through Direct Combustionof Wood Residues

A pilot plant has been established in Itoigawa, Niigata Prefecture, Japan for generation of electricity using wood as the main crop. The plant uses waste woodchips generated at construction sites, lumber from thinning of wood. The plant makes use of circulating boiler equipped with fluidized bed to burn the woodchips for effectual electricity production. The plant has a capacity to produce about 50,000 kW of electricity which could be sold to electricity retailers.

Table 2. Agriculture wastes conversion to Energy (UNEP 2009)

Agriculture Waste	Conversion process	Technology used	Type of fuel or energy produce	References
Mixed and agricultural waste	Thermochemical Process	Gasification	low or medium Btu producer gas	(UNEP 2009)
Mixed and agricultural waste	Thermochemical Process	Direct Combustion	Steam, heat,electricity	(UNEP 2009)
Municipal solid waste and agricultural	Thermochemical Process	Pyrolysis	Charcoal, synthetic fuel oil	(UNEP 2009)
Mixed and agricultural waste	Thermochemical Process	Methanol Production	Methanol	(UNEP 2009)
Wood waste pulp, sugar or starch crops,sludge rice and corn straw	Biochemical (aerobic) Process	Ethanol Production	Ethanol	(UNEP 2009)
Beanswaste, rapeseedsoy and vegetable oil	Chemical method	Biodiesel Production	Biodiesel	(UNEP 2009)

7.2. Electricity Generation Using Gasification

Community Power Corporation (CPC) has developed a down-draft biomass gasifier equipped with an inner ignition engine. The modular uses the process of gasification to generate electricity ranging between 5 kW to 25 kW using biomass fuels such as bagasse, rubber wood, palm nut shells, husks, coconut shells and wood residues. Gasification is a process in which the solid biomass fuel is converted into gaseous fuel. The gases generated are mainly hydrogen and carbon-monoxide which are burnt to produce electricity (Figure5).

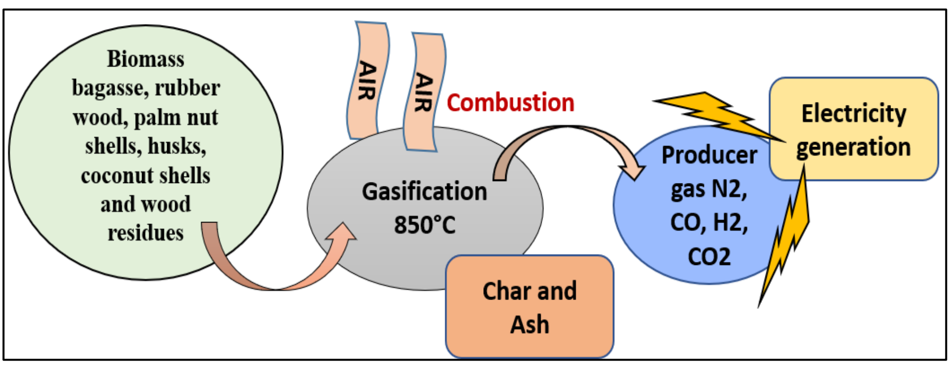

Figure 5. Electricity generation through agriculture wastes via gasification.

7.3. Production of Ethanol

Celunol, is a leading company that is involved in production and commercialization of ethanol produced from the cellulosic residues or biomass produced after processing of sugarcane and woods. The company employs technologies involving use of genetically engineered microorganisms such as *Escherichia coli*.

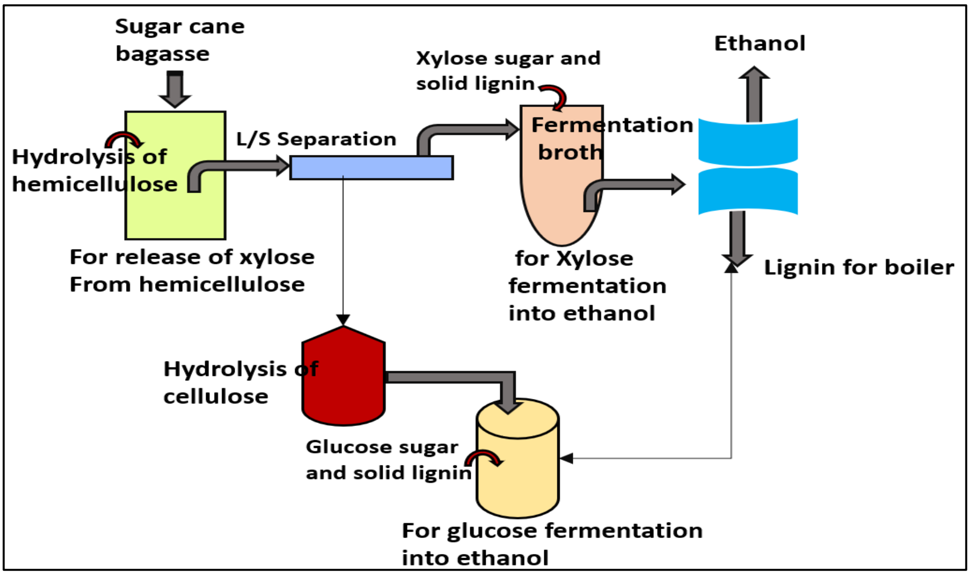

Figure 6. Production of ethanol by Celunol Corp. from waste biomass.

The recombinant bacteria ferment the cellulose, hemicellulose and all kinds of sugars present in the sugarcane bagasse and wood wastes into ethanol (Figure 6). The production of cellulosic ethanol is fuelled by lignin stream generated during processing of the same waste.

7.4. Thermal Conversion Process (TCP)

Thermal conversion process is a process that makes use of heat, water and pressure to convert agricultural waste streams, inorganic and organic food wastes into value-added products such as carbons, oils, metals, gases and ash. They also convert heavy metals into innocuous oxides. This process is used to convert feathers, bones, fats, greases into renewable energy source (diesel), chemicals and fertilizers.TCP uses air, water, oxygen, optimum temperature, pressure and suitable catalysts for conversion of cellulosic biomass to cellulosic ethanol. This method changes all the inorganic and organic constituents of the waste biomass into a synthesis gas also known as syngas. The syngas is conceded over a catalytic agent, converts the syngas into various alcohols and ethanol. In addition to usage in production of ethanol, the syngas is also used to produce plastics, synthetic petroleum products, fertilizer, and many other value-added products. It is also used as a fuel for generation of electricity.

7.5. Bio-Reduction

Bio-reduction involves conversion of raw materials such as corn cobs, wheat, pineapple plants, sugar cane, citrus pumice, rice husks and fruit drops into useful additives for beverages, ethanol, industrial absorbents and animal feed. In this process, the waste material is fed into a bio-reduction machine and ground to form slurry to extract the free water and other liquefied substances. The output after processing of the agricultural waste's releases two types of streams; one stream liquid is rich in materials that can be used as fertilizers or substrates for ethanol production (Figure 7). Second stream of liquid include solids or mechanically dehydrated compacts that could be used as animal fodder or in other value-added products.

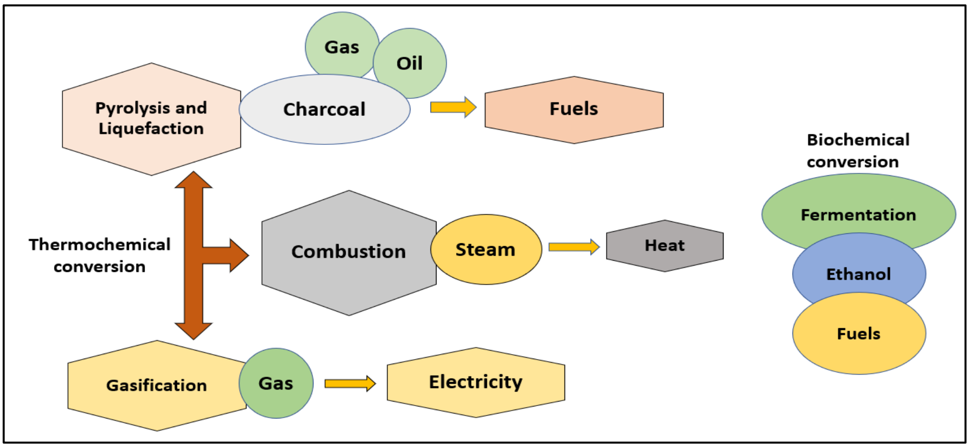

Figure 7. Cellulosic agricultural biomass waste conversion to energy.

7.6. Syntec Process

In Syntec process, the syngas produced from gasification or partial oxidation of biogas or gas released from landfills is converted into alcohols and bio-alcohols. The syngas is passed over syntec catalyst in a bed reaction unit (fixed bed reactor). Thereafter the high-quality bio-alcohols are converted to methanol, n-butanol, ethanol and n-propanol (Figure 8).

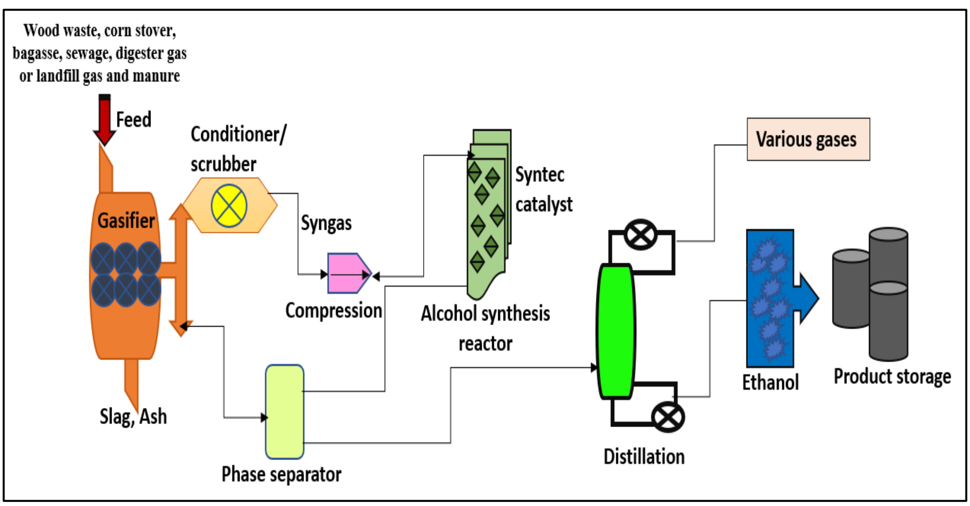

Figure 8. Production of bio-ethanol and different alcohols from syngas.

8. Conversion of Agriculture Waste Streams for Production of Value-Added Products

8.1. Cultivation of Filamentous Fungi using the by-Products of Agricultural and Food-Processing Streams

Cultivation of filamentous fungi using the by-products of agricultural and food-processing streams for production of value-added products is currently being employed. Nowadays, research is highly focused on using various microorganisms that are capable of utilizing and transforming agriculture/industrial/food-processed wastes into important components such as fuels, oil, metabolites etc. (FitzPatrick et al. 2010; Hang 1990; Mahboubi et al. 2017; Schneider et al. 2012; Van Leeuwen et al. 2010). The eradication of the waste streamlet along with transforming food-processing sewage flow and agricultural waste to worthy components for fuel applications, food and animal feed are vital steps towards taking the edge over the environmental and economic hurdles. The microbial exhaustion of organic compounds in stream renders in a considerably squeaky-clean effluent for scrapping (Sankaran et al. 2010, Van Leeuwen et al. 2012).Lipids are biomolecules involved in the formation of lipid bilayer (an integral part of the cell membrane), storage of energy (fats), regulating various signalling pathways etc. There are many microorganisms that produce and accumulate excess of lipids contributing about more than 20% of the cell biomass. These microorganisms are often called oleaginous (Ochsenreither et al. 2016).

Genus such as *Rhodosporidium*, *Trichosporon*, *Lipomyces*, *Rhizopus*, *Cryptococcus* and *Rhodotorula* consists of oleaginous yeasts that could store endogenous lipids more than 70% of their dry weight (Meng et al. 2009). Microalgae, filamentous fungi are extremely efficient in producing high oil products and polyunsaturated fatty acids (PUFAs) (Eroshin et al. 2000, Mamatha et al. 2008, Tauk-Tornisielo et al. 2009).

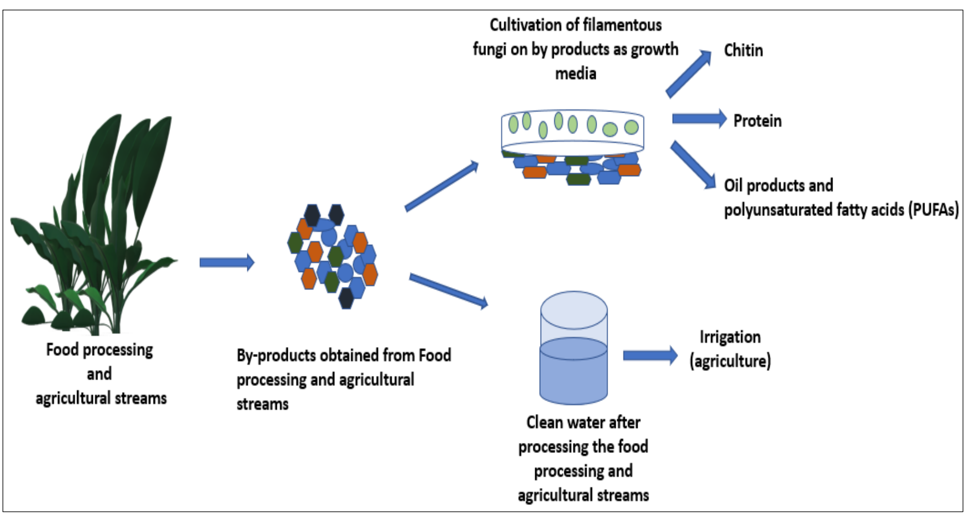

Figure 9. Conversion of agriculture waste streams for production of value-added products.

Microalgae such as *Chlorella vulgaris*, *Nitzschia* spp., *Botryococcus braunii*, *Schizochytrium* spp., are capable of CO_2 fixing and assimilation, thereby producing large amount of oils. Similarly, filamentous fungi such as *Mucor* spp., *Rhizopus* spp., and *Mortierella* spp. produces high amount of desirable fatty acids. Use of by-products generated after processing of agricultural and food waste streams could serve as substrates for culturing and cultivating microalgae, filamentous fungi, which will reduce the biological oxygen demand of the waste streams (Figure 9).

The production of microbial oil could serve as an alternative to vegetable oils used in production of biodiesel or in various food-based applications. The major advantage of using microbial oil instead of plant-based oils is that the production does not have land requirement for cultivation, neither the oil is affected by climate or season. Nowadays, biodiesel is used as an energy source which is derived from animal fats or vegetable oils. But recent studies have shown that the microbial oil can serve as a feedstock for production of biodiesel (Chen et al. 2012, Dai et al. 2007, Venkata &Venkata 2011, Wahlen et al. 2013). Despite being used in biodiesel production, microbial oils are also used in cosmetics, dietary supplements and infant nutrition’s (Ochsenreither et al. 2016, Subramaniam et al. 2010).

8.2. Oncom Production

In Indonesia, three different forms of oncom are produced. Oncom is a product produced by fermentation of agricultural wastes. The most common oncom is produced by fermentation of waste generated after processing of peanut oil. The oncum made up of peanut press-cake is called oncumkacang which is very famous in West Java (Van Veen et al. 1968; Beuchat 1986). Second famous oncom of Jakarta is oncomtahoo which is prepared from the waste generated from soya bean curd (tahoo). While, the third type of oncom is commonly known as oncumampashunkwe, is produced from waste generated after processing of starch flour (Hunkwe) and mungbean (*Phaseolusradiata*) (Steinkraus 1983).

8.3. Single Cell Protein Production

Production of single cell proteins from fruit peels was studied by (Mondal et al. 2012). They prepared a substrate of orange and cucumber peels for production of single cell proteins using submerged fermentation with the help of *saccharomyces cerevisiae*. They found that the amount of proteins produced by cucumber peels was greater than that of orange peels and could be utilized for production of single cell proteins using appropriate micro-organisms.

8.4. Activated Carbon

Activated carbon has a broad range of applications in environmental remediation, climate management, water filtration, improving crop productivity, carbon sequestration and in food industry that is attributed to its high porosity, greater surface area, reactivity and chemistry. All this makes it consummate for these purposes. It was anticipated that in 2017 the worldwide consumption of AC would reach 2.3 million metric tons (Adu et al. 2018). To accommodate the mounting demands, some unconventional sources that are not only environmentally innocuous and carbon-neutral but also have high porosity and surface area such as food processing or agriculture waste streams are needed as a substitute for customary sources, for instance; lignocellulosic materials obtained from wood and mineral carbon. For example: approximately three-quarter weight of cocoa fruit is the pod. This means that about 700-750 kg of waste can be generated from each metric ton of cocoa (Adeyi 2010). The estimated production of leading cocoa beans producing in nation like Nigeria, Ecuador, Indonesia, Brazil, Cote d'Ivoire and Papua New Guinea in 2017 was anticipated to exceed an unprecedented 4.2 million metric tons (Adu et al. 2018). In 2017, about 11.8 to 12.6 million metric tons of waste were generatedand even if a quarter of this waste could get converted into AC then it would be beyond sufficient to serve the need across the globe (Adu et al. 2018).

Two main techniques that are used more often for preparation of AC are physical activation and chemical activation. Physical activation utilizes steam or CO_2 as an oxidizing agent (Ioannidou and Zabaniotou 2007). Whereas, in chemical activation the precursor is saturated by making use of mineral salt like NaOH, KOH (Figure 10), $ZnCl_2$, H_3PO_4 or H_2SO_4 and subsequently carbonizing within a temperature range of 400°C to 800°C using microwave or in an inert condition (Deng et al. 2010).

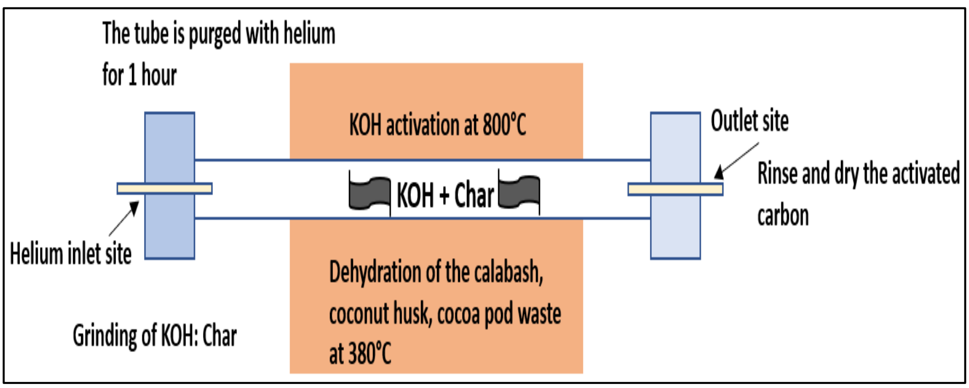

Figure 10. Production of activated carbon through chemical activation.

Numerous endeavours have been carried out to procure AC from agricultural debris/wastes as claimed by survey of reports. Various reports outline overture inspection of converting agricultural scrap like calabash, coconut husk, cocoa pod, midrib from Ghana into AC with exceptionally high surface area by employing chemical activation with ball milling and KOH. We set forth the conclusion on the pore size distribution, the surface area as a function of KOH ratio and morphology (Ioannidou and Zabaniotou 2007).

8.5. Graphene Oxide

Other important nanomaterials are graphene and graphene oxide nanosheets which posses wide applications starting from electronics, energy, sensors, environment purifications to biomedical applications. However, graphene-based nanomaterials are very costly in the existing market, which creates the main obstruction in the real-field applications. To solve this problem, recently several research groups around the world have started cost effective and large-scale synthesis of graphene oxide and reduced graphene oxide utilizing different agricultural waste-based biomass, for examples, rice husk, sugarcane bagasse, groundnut and almond shells etc.

CONCLUSION

Agro-industrial and food processing wastes or residues have high nutrient contents and bioactive composites; such waste contains compositional diversity such as sugars, proteins and minerals; thus, for most manufacturing operations, they should be called "raw material" rather than "wastes." The use of wastes generated from the food and agro-based sectors as raw materials and biomass will help to lower the manufacturing costs and lead to waste recovery, recycling, reusability and also helps in reducing contaminants that are hazardous for the environment and human health.The proper management of agricultural wastes by following the agricultural waste management systems using "3Rs" approach would be quite beneficial for both in developing value-added products for humans and in reduction of environmental pollution generated by random disposal of agricultural wastes carelessly. Proper use of wastes would help to grow our agriculture sector and provide a viable resource for production of biofuels, energy, electricity, heat etc.

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Chapter 5

ANALYSIS OF THE EVOLUTION OF URBAN SOLID WASTE MANAGEMENT IN 10 MIDDLE INCOME GEOGRAPHIC REGIONS: A MINI-REVIEW

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ABSTRACT

The paradox between high consumption and high waste generation has stimulated scientific studies in the area of urban solid waste management (USWM). Therefore, the present study is characterized for being a mini literature review whose main objective is to discuss and identify aspects related to the evolution of USWM in 10 geographic regions (GR) of middle income: Cairo, Yaoundé, Kinshasa, Managua, São Leopoldo, China, Madhya Pradesch, Tha Khon Yang, Allahabad and Sri Lanka. The study was based on approaches from 61 scientific references (52 scientific articles, 2 books, 2 book chapters, 2 political regulating instruments of and 3 international databases. The research problem was synthesized in the question: "What is the level of GR adherence to priorities established in the 3 phases of the evolution of USWM addressed by Demajorovic (1995)?" The results showed that only 10% of GR have High Adhesion, 20% have Average Adhesion and 70% are part of the group of No Adherence to the priorities

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established in the phases of Demajorovic (1995). The data confirm that 70% of GR have a delay of almost 60 years in USWM processes. The analysis offers a double contribution to the literature and to the decision of public and private managers. Firstly, by making them realize how far the USWM is from a sustainable path, and secondly by helping them reflect on how to handle the difficulties that hinder USWM evolution.

Keywords: waste, urban solid waste, urban solid waste management, developing countries, geographic regions, sustainable waste management

1. Introduction

The current economic model strongly stimulates the consumption of disposable products regardless of the real need of the consumer and despite the threat of resources scarcity. The reflection of this consumerist logic, directly affects the increase of the generation and waste disposal rates, forcing countries to rethink their urban solid waste management (USWM) models. In this context, we live in a paradox, where the damage caused by the increasing waste generation is known. However, restrictive forces such as individual habits, the absence of effective policies and scarce financial resources represent bottlenecks for behavioral change towards pro-environmental consumption, namely in developing countries.

The absence of sustainability-based USWM has impacts on society (harm to public health), on the economy (resource scarcity) and on the environment (air, soil and water contamination) (Patel, Jain and Saxena, 2010). Within this context, the high-income countries, which until the 1960s were limited to waste collection, began to discuss the evolution of USWM policies (between the 60s and 70s) in their agendas. The initial focus was finishing the deposit and the burning of waste in open spaces, and for later focus (1980s), the use of waste as a resource in the production process (Singh et al., 2014).

USWM policies in developed or high-income countries were driven by different priorities and contexts that may be established in 3 phases, mentioned in Demajorovic (1995).

Phase 1 (1960s until mid-1970s): the proper final disposal of waste became a priority, so most OECD countries managed to eliminate dumps by starting to dispose of their waste in landfills or incinerators.

Phase 2 (mid-70s to 80s): when the disproportionate waste generation in relation to the availability of spaces for final disposal and the constant incineration processes aggravated the environmental impacts.

This prompted the OECD countries, in 1975, to publish a list of priorities in this field, such as reduction of generation, material recycling and stimulation of the recyclables market, incineration with energy reuse and finally the waste disposal in landfills.

Phase 3 (late 1980s to 1990s): when the first criticisms of the recycling system arose and new priorities were established such as reduction of generation, preference for reuse of recycling and energy use of the waste before its disposal to the landfills.

It should be noted that the emergence of a new cycle of priorities, or new phases, was due to the flaws found in the processes adopted in the previous phases, and it was in this context that changes in policies and regulatory instruments emerged, for a more preventive perspective, confronting the linear and traditional USWM model.

In this framework, the developed (high-income) countries of the European Union, the United States and Japan, between the 1960s and 1970s, started to regulate the waste sector (Juras, 2012). They focused on restructuring the policy instruments that began to prioritize a preventive stance, with the aim of reducing the impacts at socio-economic-environmental levels, as well as having an innovative outlook in terms of the development of technologies that capture the opportunities offered by the sector. The pioneering role of developed countries in the evolution of USWM may be due to the existence of the technical and financial capacity associated with high waste generation rates. Developing countries (low and middle income) had different contexts at that time, due to their technical and financial capacities. Many of them, at present time, are still trying to overcome prioritized problems from the 70s (Guerrero and Erbiti, 2004). A large part of the studies developed make approaches related to diagnosis or management assessment in specific locations, and other studies propose assessment models for future application. From the analysis of some studies, several methodologies have been used by the researchers, as shown in Table 1.

Most of the aforementioned studies aimed to analyze the performance of USWM, and in order to do so, the use of indicators or one of the mentioned methodologies was fundamental. Among the contributions of these approaches, is measuring the degree of efficiency of the management processes, allowing to quantitatively analyze the USWM performances of one or more regions.

The present study has the objective of answering the question: "What is the level of adherence, of different geographical regions, to the priorities established in the phases addressed by Demajorovic (1995)?". To address this question, the following steps were followed: (i) discussion and identification of aspects related to the evolution of USWM in different geographic regions; (ii) analysis of the context of USWM in specific geographical regions showing the most recurrent aspects related to weaknesses and opportunities and (iii) classification of geographical regions at the level of adherence to the priorities established in the three phases of Demajorovic (1995), considering the time when the information from the Geographic Region (GR) was produced in the scientific references used. The name Geographic Region - GR in this study, is used to delimit an analyzed area, which may correspond to a country, a state or a developing municipality.

The associative approach of the USWM context of the GR in the Demajorovic (1995) phases, is the contributory differential of this paper, both for the scientific community to more broadly understand the advances and bottlenecks inherent to the USWM of the selected GRs, as well as for the managers and policymakers who may adopt practices and policies capable of overcoming the priorities established in the three phases highlighted by Demajorovic (1995).

This paper is divided into 5 sections including this introduction. The following section presents the methodological procedures; the third section presents conceptions about the solid urban waste sector, aspects, implications and management models in developed and developing countries; the fourth section deals with the synthesized analysis of USWM contexts of ten geographic regions and their division into groups; and finally, in the fifth section, the final considerations, the limitations of this research and future approaches for a deeper insight into this theme are proposed.

Table 1. Studies and Methodologies for the evaluation of USWM

Researchers	Article Title	Methodology	Application Location
Alesch and Brunner, 2014	Assessment methods for solid waste management: A literature review	Cost Benefit Analysis (CBA)	--
Chen, 2010	A performance evaluation of MSW management practice in Taiwan	Data Envelopment Analysis (DEA) and Analythical Hirarchical Process (AHP)	Taiwan
Chifari, et al., 2017	Development of a municipal solid waste management decision support tool for Naples, Italy	Multi-Scale integrated analysis of societal and ecosystem metabolism (MuSIASEM)	Naples/Italy
Fratta, Toneli and Antonio, 2019	Diagnosis of solid urban waste management in the cities of ABC Paulista do Brazil through the application of sustainability indicators	Sustainability Indicators	São Paulo/Brazil
Fragkou, Vicent and Gabarrel, 2010	A general methodology for calculating the MSW management self-sufficiency indicator: Application to the wider Barcelona area	Material Flow Analysis (MFA)	Barcelona/ Spain
Guerrero and Erbiti, 2004	Indicadores de sustentabilidad para la gestión de los residuos sólidos domiciliarios	Sustainability Indicators	Tandil /Argentina
Gonzalez-Garcia et al., 2018	Assessing the sustainability of Spanish cities considering environmental and socio-economic indicators	Life Cycle Analysis (LCA) Material Flow Analysis (MFA)	Spain
Karmperis et al., 2013	Decision support models for solid waste management	Life Cycle Analysis (LCA)	--
Silva et al., 2017	Multidimensional Indicators of Integrated Solid Waste Management Policies of the Brazilian capitals: overview from 2008 to 2014	Use of Indicators	Brazil
Pereira, Curi and Curi, 2018a	"Use of Indicators in GRSU: a methodological proposal for the construction and analysis of for municipalities and regions"	Evaluation Indicators	--
Pereira, Curi and Curi, 2018b	Use of Indicators in GRSU: part II - a methodological proposal for the construction and analysis of for municipalities and regions: application of the model	Evaluation Indicators	Campina Grande/ Brazil
Reis, Mattos and Silva, 2016	Urban solid waste management in municipalities in Brazil: A review of evaluation methods	Systematic literature review	Brazil
Rigamont, Sterpi and Grosso, 2016	Integrated municipal waste management systems: An indicator to assess their environmental and economic sustainability	Use of indicator	Lombardia/ Italy
Traven, Kegalj and Sebelja, 2018	Management of municipal solid waste in Croatia: Analysis of current practices with performance benchmarking against other European Union member states	Robust Regression and Outlier Removal	Croatia
Vishwakarma et al., 2012	Efficiency evaluation of municipal solid waste management utilities in the urban cities of the state of Madhya Pradesh, India, using stochastic frontier analysis	Stochastic Frontier Analysis (SFA)	Madhya Pradesch/ India
Zaman, 2014	Measuring Waste Management Performance using "Zero Waste Index": The Case of Adelaide, Australia	Zero Waste	Adelaide/ Australia
Yadav and Samadder, 2018	A critical review of the life cycle assessment studies on solid waste management in Asian countries	Literature Review	Asia
Zaman, Shahidul and Swapan, 2017	Performance evaluation and benchmarking of global waste management systems	Zero Waste	Global analysis: 168 countries

2. METHODOLOGY

This study is a literature review of exploratory and qualitative nature. Given the complexity of the subject and the several approaches, data collection was based on scientific articles published (mostly in the last 10 years), regulatory instruments on the subject and statistical data from world organizations.

The main database used was the Scopus Platform and two procedures were adopted to choose the articles: firstly, a survey, and secondly, a selection. The criteria established for the first procedure was based on the combined use of four groups of keywords: (a) solid waste, urban solid waste management and countries; (b) urban solid waste management, evaluation and indicators, (c) urban solid waste management, policies and implementation and (d) waste management, challenges, barriers and opportunities. Refinement was applied at the survey stage, limiting to journals of general approaches on USWM. For the execution of the second procedure, the title and the summary content of the articles were considered, aiming to select the research whose approaches were related to the analysis of the USWM status in different geographical regions.

In addition to the Scopus platform, articles from the Web of Science database and the ResearchGate System were used in this research resulting in a total of 52 scientific articles and 2 book chapters. 2 USWM regulatory instruments, 3 international databases (Eurostat, UN and World Bank) and 2 books of the UN (containing definitions and projections of the waste sector for the years 2030 and 2050) were also incorporated into the references.

To meet the specific objectives of this research, 10 geographic regions were selected and analyzed. The selection of geographic regions was based on two criteria: i. be or belong to a middle- or low-income country and ii. the availability of information related to the diagnosis of USWM processes. The selected regions were: Allahabad, Cairo, China, Kinshasa, Managua, São Leopoldo, Madhya Pradesch, Sri Lanka, Tha Khon Yang, and Yaoundé.

Due to the qualitative nature of this study, we do not intend to quantitatively evaluate the performance of USWM in the frame of some of the methodologies mentioned in the introduction. Based on the level of adherence to the priorities established in phases 1, 2 and 3 by Demajorovic (1995), this paper proposes the classification of Geographic Regions into 4 groups:

- High Adhesion: managed to overcome the aspects prioritized in phases 1, 2 and 3;
- Average Adhesion: managed to overcome the aspects prioritized in phases 1 and 2;
- Low Adhesion: managed to overcome the aspects prioritized in phase 1
- No Adhesion: failed to overcome the aspects prioritized in any of the 3 phases

The analyses in the fourth section of this study were divided into four stages: (i) identification of the GR/Location/Scientific Reference, (ii) synthesizing the main aspects highlighted in the scientific references, (iii) identifying the most recurring aspects in the USWM of the GRs (weaknesses and opportunities) and (iv) reflections on the context of USWM of the GRs and verification regarding adherence level to the priorities established in the 3 phases of approach by Demajorovic (1995).

3. Theoretical Framework

3.1. Concepts and the Importance of Waste Management Sector

The evolution of debates in the waste sector makes it possible to understand the concepts that this sector involves, and also drives the development of appropriate guidelines to minimize the effects provided by the evolution of generation rates. Therefore, before discussing the appropriate management model for this sector, the processes that involve it and the reflexes of uncontrolled waste generation, it is important to understand some consolidated concepts. The European Union (EU) Directive 2008/98/EC in its 3rd article defines waste as "any substance or object which the holder discards or has the intention or obligation to discard". This definition would, in principle, encompass waste in its three forms: liquid, gaseous and solid. Discarding or disposal may represent waste of resources and energy and/or increased environmental impacts. To restrict the discussion of waste in its solid form, it is pertinent to present the United Nations definition, available in Chapter 21 of Agenda 21 (1992): "Solid waste, includes all domestic and non-hazardous waste, such as commercial and institutional waste, sweeps of streets and construction debris."

Other definitions are linked to the reality of municipalities: "Municipal waste consists of waste collected by or on behalf of competent authorities and disposed of through established waste management systems, and from which the following would be excluded: sewage waste treatment, construction activities and demolition" (Halkos and Petrou, 2016). Another important definition is given by (Elsaid and Aghezzaf,2015, p.2), saying "Urban Solid Waste (USW) as waste generated from residential, commercial and institutional areas that include homes, offices, schools, shops, etc".

The complexity of the processes, involving the solid urban waste sector and the need to balance these processes, requires the implementation of adequate management models, as well as an understanding of the concepts associated with management. In this sense, the Directive (98/2008/EC) defines USWM as the collection, transportation, recovery and disposal of waste, including the supervision of these operations, the maintenance of disposal sites after closing and the measures taken as a trader or broker.

In order to adapt to the evolution of new concepts and guarantee the efficiency of USWM, high-income countries were the pioneers in including the waste agenda in their political agendas (Singh et al., 2014).The most recurrent consequences of an inefficient USWM are mentioned by several researchers: damage to public health (Ghesla et al., 2018; Alfaia, Costa and Campos, 2017); expansion of consumption (Srivastava et al., 2015; Patel, Jain and Saxena, 2010); scarcity of resources to meet high consumption; rising rates of waste generated by population explosion in urban centers (Srivastava et al., 2015; Patel, Jain and Saxena, 2010) and scarcity of land for waste disposal (Banerjee and Sarkhel, 2020).

Inadequate waste management affects recycling processes, treatment technologies and management strategies defined for a given location, leading to economic losses, threatening public health and the environment (Abduli, Tavakolli and Azari, 2013). Inadequate MSW collection and management practices also result in the loss of resources and energy since recycling initiatives are not foreseen (Damghani et al., 2008; Jiang et al., 2009).

Another major problem caused by USWM inefficient processes is the increase in waste generation rates. It is predicted that by 2050 the generation of waste in low and middle-income countries will increase by 40%, and 19% in high income countries (Kaza et al., 2018). The data reveal the importance of discussing this issue, and reinforces the desperate need to expand effective actions to contain the volume of waste generated in the world.

3.2. Generation of Urban Solid Waste: Evolution and Implications in USWM

The world average of daily generation per person is equivalent to 0.74 kg, but varies widely, from 0.11 to 4.54 kg and this variation is explained by the positive correlation between waste generation and the income of the country. In 2016, world generation was about 2.01 billion tons, with 33% of the volume generated being inadequately managed and 16% of the world population, which makes up high-income countries, were responsible for generating 34% of the total of this waste (Kaza et al., 2018).

Population growth directly implies an increase in the generation of waste and it is expected that by the year 2050 the rate of world generation will reach the level of 3.40 billion tons of waste (Kaza et al., 2018). This scenario threatens the sustainability of the urban environment, as there will be a greater demand for territorial spaces to house the volumes generated and the new population contingents, which will make systems for final disposal of waste (such as landfills), more expensive (Banerjee and Sarkhel, 2020; Alfaia, Costa and Campos, 2017).

With the urban population growth, high-income countries have implemented policies and measures to stabilize the rates of waste generation, yet still have a significant waste rate when compared to middle and low-income countries. (Singh et al., 2014). The guidelines and policies that changed USWM in high-income countries unfolded gradually and were directly dependent on the context of each country at the time the priorities for USWM were determined.

The 1970s represented a milestone for changes in USWM, when approaches were focused on controlling the accumulation of waste in landfills (waste cover and compaction) and incinerators (dust and leachate control). The control of by-products (gases and slurry), from waste accumulation, were only prioritized in the 1980s by the implementation of improvements in technical management standards (Brollo and Silva, 2001).

Although the primary problems of USWM (collection and disposal) were overwhelming in high-income countries, the global impacts of USW generation persisted, and in the 1990s, new priorities were introduced into the traditional USWM model and an integrative USWM was proposed.

In this new proposal, besides the environmental aspect (the main focus ~~of~~ in previous decades), the political, economic, financial and social aspects were also considered (Marshall and Farahbakhsh, 2013; Brollo and Silva, 2001). The new requirements for USWM suggest a radical change in the traditional model in favor of an ecological cycle management perspective Moreover, this perspective, requires setting up a circular system where utilization is preferable to the final disposal of USW (Demajorovic, 1995). This new management perspective confronted the traditional models that had prevailed for several decades and were based on the linearity of the waste treatment flow, in the following order: generation, collection and final disposal. In terms of sustainability, the linearity of material flows is one of the biggest problems cities face (Fragkou, Vicent and Gabarrell, 2010), and reflects the form of consumption, where resources entering the human environment are processed, used and disposed of, in nature, as solid, liquid and gaseous wastes (Singh et al., 2014).

3.3. The Unsustainability of the Linear Waste Management Model

The linear model of USWM predominated worldwide in the years before the 1970s. The decline of this model was evident initially in high-income countries, given the scientific evidence of its incompatibility with new contexts. In middle and low-income countries, the linear model is still prevalent and, in many cases, it operates with low efficiency. Despite the evolution of debates on the need to adapt the USWM model, the implementation of new practices, still focus more on reducing impacts than on prevention, suggesting "pipe end" solutions to waste over long term sustainable alternatives (Singh et al., 2014 apud Seadon, 2010).

The traditional linear USWM, the population boom of the last 20 years and the economic progress have resulted in the expansion of waste, (Patel, Jain and Saxena, 2010). The traditional models are ineffective for the new reality arising from economic progress, raising concerns about the scarcity of resources caused by the high demand of industrialization processes.

In this context, representatives of developed and developing countries are under pressure to re-evaluate their public policies and their USWM models in order to achieve impact reduction through the implementation of more sustainable models (Halkos and Petrou, 2016).

The sustainability of USWM in all its stages and the development of new treatment technologies that can ensure meeting global sustainability goals is a strong requirement of the 21st century (Pires, Martinho and Chang, 2011). The Agenda 2030, prepared by the United Nations (UN), is one of the global instruments that set sustainability goals materialized in objectives to be met by nations in various sectors, including waste. Although the objectives defined by this instrument are common to countries, their contemplation requires different challenges and the economic, social, political and environmental context defines the challenges to be faced by each country (Yukalang et al., 2018).

Factors such as territorial extension, citizens' environmental awareness and development, directly influence the USWM of each nation (Guerrero and Erbiti, 2004).

One of the major global contributions for changing the design of waste, giving it value and suggesting an order in waste treatment, is presented in the 4th Article of Directive (EU) 2008/98/EC. It provides for waste hierarchy to be applicable as a general principle of prevention, management legislation and policy, whose order of treatment would be: 1st, prevention and reduction; 2nd, preparation for reuse; 3rd, recycling; 4th, other types of recovery, such as energy recovery and 5th elimination. The European waste hierarchy proposal has influenced and influences the design of regulatory instruments aligned with the principles of sustainability. However, many countries, especially developing countries, face difficulties with the implementation (Cetrulo et al., 2018), either due to insufficient financial or technical capacity, or because of not prioritizing the issue in their political agendas.

In conclusion, in view of the above, the assessment of the USWM context in the countries is crucial to identify the priorities established in the different phases of evolution of the USWM.

3.4. USWM Context in Developed and Developing Countries

USWM in an environmentally accepted, safe and sustainable manner must be a top priority of any modern country or society. Learning, based on successful experiences from developed countries, is important for neutralizing weaknesses in developing countries' USWM. Two factors were important in driving the setting of rigid EU targets for reducing landfill waste rates, namely: awareness of the economic value of waste and environmental concern. Reflections of the EU targets resulted, between 1995 and 2008, in the reduction of rates from 62% to 40% (Fischer, 2011).

Germany's closed-loop management policy aimed at transforming waste management into resource management and has indeed succeeded in replacing 14% of its raw materials in industries with recovered waste. Moreover, in this country, since 2005, waste cannot be directed to landfills without first undergoing treatment methods such as recycling, incineration and/or composting (Nelles, Grünes and Morscheck, 2016). According to data from EUROSTAT (2016), Germany is the EU country that most submits its waste to treatment, with France and Italy occupying the second and third positions in this category, respectively. Despite being oriented by the same USWM directives established by the European Union, countries with lower treatment rates still have the grounding of their waste as their main method.

Unlike the reality of the EU, developing countries lack adequate planning and financial resources (Fernando, 2019; Gonçalves et al., 2018). In addition, political neglect of USWM issues has accentuated environmental problems and affected public health (Srivastava et al. 2015; Saxena, Srivastava and Samaddar, 2010).

The city of Allahabad, located in India, has weaknesses in the collection processes, and it is common to see waste disposed outside the doors of homes and commercial establishments for days. In addition, the waste that is collected is deposited in dumpsites. (Saxena, Srivastava and Samaddar, 2010) A similar scenario occurs in the main cities of Pakistan where USWM is restricted to urban areas, with no waste collection system in rural areas. Bottlenecks such as the lack of financial resources, collection and transportation facilities, as well as specific final disposal sites make sustainable waste management unfeasible. (Batool, Chaudhry and Majeed, 2008)

Although the implementation of a sustainable USWM is recommended by the United Nations to all countries, the disparities between developed and developing countries are evident. For example, while Germany manages to divert almost all of its waste from landfills, reintroducing it into the production chain (Traven, Kegalj and Sebelja, 2018), some developing regions have a clear inability to collect their waste, such as Cameroon-Africa (Parrot, Sotamenou and Dia, 2009) and Cairo-Egypt (Elsaid and Aghezzaf, 2015).

Within developing countries, the Asian continent has received strong pressures to adapt its USWM models, especially due to the high percentages of waste generation. South and East Asia alone are responsible for the generation of 33% of the world's total waste (Srivastaza et al., 2015).

Considered to be the largest waste generator, China has always been pressured by international institutions to adapt its USWM model. In 1996 the first Chinese waste policy was promulgated - People's Republic of China Law on the Prevention of Environmental Pollution from Solid Waste (Solid Waste Act) and, over time, important amendments have been incorporated into this instrument to: control pollution, foster the recyclables market, extend producer responsibility, reduce generation, create the concept of an ecological city, charge for plastic bags and establish the Circular Economy Promotion Act (Chen, Geng and Fugita, 2010). Although it has a sustainable regulatory policy framework, the Chinese USWM still has gaps and disparities due to the unequal distribution of financial resources, justifying the different performances of Chinese municipalities (Chen, Geng and Fugita, 2010).

India, the second most populous country in the world, faces a very different reality from China, mainly due to the latent neglect of Indian governments to USWM issues. Primary services, such as coverage and disposal are inefficient (Srivastava et al., 2015).

The unavailability of adequate facilities to treat and dispose of large quantities of MSW is one of the major problems facing metropolitan cities in India (Saxena, Srivastava and Samaddar, 2010). Despite the fact that the situation is critical in most Indian municipalities, some cities follow the National Regulations enacted in the 2000s and have consequently won awards for their USWM status, such as Namakkal located in Tamil Nadu State (considered the zero-waste city) and Suryapet located in the state of Telengana (which stood out for introducing the door-to-door collection system) (Saxena, Srivastava and Samaddar, 2010).

The reality of Korea can be referred to as another example in Asia. The country faces barriers concerning the adequacy of USWM, moreover, it does not have sufficiently clear policies as the approval of recycling projects is complex (Um et al., 2018).

Problems related to the implementation of the National Waste Policy are also faced by Sri Lanka, who had even approved this policy in 2007. This country faces recurring barriers, such as resource scarcity, equipment unavailability, low awareness of citizens, poor understanding of the benefits of national policy, the absence of regulatory and control mechanisms, the unavailability of the market for recyclables, the demotivation of staff involved in USWM, and political instability (Fernando, 2019).

The enactment of the National Waste Policy has not been sufficient to ensure USWM efficiency in developing countries such as Brazil (Cetrulo, et al., 2018), Cameroon (Parrot, Sotamenou and Dia, 2009), Korea (Um et al., 2018), Sri Lanka (Fernando, 2019) and India (Saxena, Srivastava and Samaddar, 2010). This fact suggests that despite having legal importance and quality, the enactment of the law alone does not ensure improvements in the management of USW (Ghesla et al., 2018), hereby requiring the monitoring and identification of intervention needs (Cetrulo et al., 2018) to achieve the objectives set by the legislative instrument.

The American continent should also be analyzed, as it has two countries with high levels of waste generation. Brazil for example, is the fourth largest waste generator in the world, behind China, the United States (USA) and India (Silva, Fugii e Santoyo, 2017). Unlike the US, Brazil is a developing country and, although it is the 12th largest economy in the world and has already enacted its USWM policy for almost 10 years (Law 12.305/2010), it has not yet managed to address USWM primary problems. Most of its municipalities have deficiencies in collection, treatment processes and final disposal. An intrinsic factor in this country is the physical and structural distance between government standards and guidelines and what is implemented in reality (Maiello, Britto and Valle, 2018).

In 2017, of total waste volume collected in Brazil, 40,9% was directed to unknown or inappropriate locations. 3,352 Brazilian municipalities deposit their waste in inadequate final disposal systems (Ghesla et al. 2018). Data from the Institute of Applied Economic Research

(IPEA), released in 2010, highlights that by neglecting the potential of recyclable waste and landfilling them, Brazil wastes US$3 billion per year (Costa, Costa and Freitas, 2017).

Due to its economic development, Brazil can be compared to some developed countries, but in most of its territory, the quality of USWM is as poor as in low-income countries, such as in the city of Aurora-Ceará, Campina Grande-Paraiba and Cuité – Paraiba (Moreira et al., 2017) The most significant deficiencies identified are in primary processes such as collection and transportation, irregular disposal, frequency, inequality and collection coverage, lack of selective collection, with this being more critical in rural areas (Cetrulo et al., 2018). Despite this scenario, some Brazilian municipalities, especially those in the more developed regions (Southeast and South), have evolved and introduced more advanced technologies and procedures for their USWM, such as in the city of São Leopoldo, which has an intensive selective collection program and has 5 sorting centers responsible for boosting the recyclables market (Ghesla et al., 2018).

Although the United States is a developed country and has technologies for reuse, it still lacks in this regard. Data from the Environmental Protection Agency (EPA) released in 2016, revealed that the shipment of MSW to landfills in 2015 reached 52.5% and reuse activities had the following percentages: incineration with energy recovery 12.8%, recycling 25.8% and composting 8.9% (Paes et al., 2019).

When analyzing Central America, the city of Managua-Nicaragua stands out for having challenged the logic of the centralized USWM system in developing countries. By favoring ideas imported from agencies, international consultants, and other political actors, Managua opened up projects for international Nongovernmental Organizations and encouraged community members to carry out the collection service, benefiting areas that are inaccessible to transportation, and building waste transfer stations. These stations and decentralized collection practices, driven by the Department of International Relations, challenged the logic of the centralized USWM system and offered the possibility of reducing the costs of this activity by up to 50% (Campos and Zapata, 2014).

Another geographical region that deserves attention is Thailand, that in 2014 established its Roadmap for Municipal and Hazardous Waste, delegating the USWM responsibility to local governments. However, several problems have hindered the successful adaptation of USWM, especially as most municipal governments, in addition to not having local regulations, are focused on other demands, such as water and sewage infrastructure, road maintenance, utilities and disaster response. In 2016, only 60% of municipalities in Thailand provided a collection service and of this, only two thirds directed their waste to landfills (Yukalang et al., 2018).

The reality of Cairo, capital of Egypt, also lacks legislation, with no prohibition on the disposal of garbage in inadequate systems, with 83% of waste going to landfills. Another major difficulty faced by this region is the lack of data on USWM processes (Elsaid and Aghezzaf, 2015).

Still regarding the USWM disparities involving developed and developing countries, urban and rural areas, another type of disparity was identified in the urban area of the city of Kinshasa, the capital of the Federative Republic of Congo. USWM service delivery is offered with severe discrimination, ignoring the poorest locations, a scenario that suggests the need for approaches that link social and environmental justice with USWM issues (Kubanza and Simatele, 2016). The poor urban population of Kinshasa, burdened with the weight of solid waste, with no voice or vote, associated with lack of knowledge to deliberate on complex issues involving USWM, are notoriously undermined which ultimately strengthens the labels “racism and environmental discrimination” in this city (Kubanza and Simatele, 2016). Congo also faces difficulties in the provision of primary services, and in this context, the population living in poorer areas is daily subject to unhealthy and precarious conditions, due to the lack of waste collection.

The deficiencies identified in developing countries reinforce the need for further study to understand the status of USWM as well as to enable more assertive interventions.

4. Results and Discussion

4.1. Synthesized Analysis of USWM Context in Different Geographic Regions

The synthesized analysis was divided into 4 stages: i. selection of geographic regions to be analyzed (table 2); ii. identification of the main aspects of the USWM of each GR (table 3); iii identification of the most recurrent aspects of USWM in terms of weaknesses and opportunities (tables 4 and 5) and iv. classification of GR according to the level of adherence to the priorities established in the 3 phases of Demajorovic (1995) (table 6).

4.1.1. Step 1: Identification of GR/Location/Scientific Reference Used

The definition of the GRs was based on the availability of articles selected for this research, with specific and detailed approaches on Urban Solid Waste Management. Of the 61 references used in this research, 10 comprised this topic and all considerations made here, consider the time when the research was developed. The selected GRs correspond to a group of (2) developing countries, (1) state and (7) municipalities (all located in developing countries). Among the 7 municipalities, 4 of them are capital cities of their countries.

Table 2. Geographic Region Data and Reference Adopted for analysis

GR	Category	Location	Classification of the country _ income*	Reference	
				Authors	Year
1. Allahabad	Municipality	India (Asia)	Lower-middle Income	Saxena, Srivastava and Samaddar	2010
2. Cairo	Municipality/ Capital	Egypt (Africa)	Lower-middle Income	*Elsaid* and *Aghezzaf*	2015
3. China	Country	(Asia)	Upper-middle Income	Chen, Geng and Fugita	2010
4. Kinshasa	Municipality/ Capital	Congo (Africa)	Lower-middle Income	Kubanza and Simatele	2016
5. Madhya Pradesch	State	India (Asia)	Lower-middle Income	Patel, Jain and Saxena	2010
6. Manágua	Municipality/ Capital	Nicaragua (America)	Upper-middle Income	Campos e Zapata	2014
7. São Leopoldo	Municipality	Brazil (América)	Upper-middle Income	Ghesla *et al*	2018
8. Sri Lanka	Country	Asia	Upper-middle Income	Fernando	2019
9. Tha Khon Yang	Municipality	Thailand (Asia)	Upper-middle Income	*Yukalang, Clarke and Ross*	*2018*
10. Yaoundé	Municipality/ Capital	Cameroon (Africa)	Lower-middle Income	Parrot, *Sotamenou*, and *Dia*	2009

Source: Prepared by the authors, 2020.

The GRs are distributed among 3 continents (Asia, Africa and America). The analyzed regions comprise, or are countries classified by the World Bank (2020), as middle -income: (5) upper-middle income and (5) lower-middle income, as shown in Table 2.

4.1.2. Step 2: Synthesizing the Key Aspects Highlighted by the Authors (Fragilities and Opportunities)

In this step, the main aspects of the USWM were briefly presented and the weaknesses or opportunities were classified, according to Table 3. The presented synthesis takes the information and data present in the selected references for each region into account.

4.1.3. Step 3: Most Recurring Aspects in USWM of GRs (Weaknesses and Opportunities)

In the third step, the most recurrent aspects of USWM were identified, classifying them into aspects of weaknesses (Table 4) and into aspects considered as management opportunities (Table 5). One of the objectives of this step was to identify the percentage of the presence of each aspect in the regions, based on the sum of the recurrences of each one. The other objective was to highlight the regions with the greatest number of aspects, both of weaknesses and of opportunities, from the sum of the aspects present in each region.

4.1.4. Step 4: Reflections on the USWM Context of the GR and the Priorities Established in Demajorovic's Phases

Tables 4 and 5 present a synthesis of the most recurrent aspects of USWM in each GR and these were based on the information in Table 3. When accounting for the presence of recurrent factors, it was identified that the GRs - Cairo, Yaoundé, Kinshasa and Tha Khon Yang, are the regions that have the most weakness factors and the regions of Managua, Saint Leopold and China are the regions that have the most opportunity factors.

As it is a country, rather than a smaller region such as a municipality or state, China has shown contrasting results, as it reveals locations with improved performance and others with significant deficiencies in its USWM. For this reason, when considering China's advances, the condition "not in its entirety" is mentioned.

The results in percentages show that 80% of the GR had ineffective programs for the USWM, with São Leopoldo and China being excluded from this list~~.~~ (not in its entirety). Collection is ineffective in 90% of the GR and selective collection initiatives are absent in 70% of them. Only 40% of the GR have recycling projects, 30% use the landfill and only 20% compost. Factors related to ineffective technology and waste picker informality are present in 90% and 100% of GRs respectively. Regarding government support for USWM improvement projects and international support, only 30% and 20%, respectively, of the GRs, benefit from this support. Concerning environmental awareness, it was found that it is present in only 30% of the GR, and the scarcity of resources for the management of MSWs was found in 90% of the regions. Although 60% of the GR integrates countries with legislation that is adequate to sustainability principles, the results suggest an unsuccessful implementation of the laws.

Table 3. Synthetic Analysis of Geographic Regions (GR)

Author/Year **GR**	**Weaknesses of urban solid waste management**	**Opportunities/suggestions for urban solid waste management**
Saxena, Srivastava and Samaddar, 2010 **1. ALLAHABAD** Índia Ásia	• USW is directed to dumps • Waste burning is a common practice • The health and engineering departments are responsible for USWM • Waste collected is transferred to designated collection points in nearby wheelbarrows or dump trucks • Absence of joint procedure for USWM from residential as well as commercial areas • Charging fees for generators is unavoidable • Poor financial conditions of the population • Informal waste picker sector is disorganized • Recyclable and compostable revenue is below the capacity of the sectors • 43.46% of MSW is organic in nature	• USWM Strategic Planning • Adequacy of collection and disposal systems • Creation of the Secretary of the Environment • Establishment of Legislation prohibiting harmful actions • Environmental education for population awareness • Encourage the organization of waste pickers by giving them the technical and infrastructure conditions to carry out selective collection. • Encourage waste separation at source • Encourage composting and recycling
Elsaid *and Aghezzaf, 2015* **2. CAIRO** Egypt Africa	• Absence of Environmental Policies • Legislation with reduced applications • Absence of technology and technical capacity • 83% of Waste is landfilled and burned • Outsourcing in 2003 to European companies for waste collection (fixed points) and transport services • Tax collection for the provision of these services on the electricity bill • Tariff harmed waste pickers previously paid by residents to collect (door-to-door waste) and sell recyclable waste • Waste separation process carried out by informal waste pickers on public roads or dumps in poor and unhealthy conditions • Waste mixed with hospital waste reducing the potential of recyclables and making the recycling process more expensive • Ineffective outsourced processes • Scarce financial resources • 20% of the population is in the poverty line, which makes it impossible to pay fees for the provision of USWM services • Lack of reliable data and difficulties to access by poor collection methods	• Establishment of clear and appropriate policies to the sustainability precepts. • Actions to promote community behavior change from greater environmental awareness • Outsourcing USWM services to European companies in countries lacking technical or technological capacity, however these services need to be supervised to ensure efficiency • Organization of waste pickers in cooperatives or other models of organizations that promote selective collection and guarantee healthy conditions for these collaborators • Waste pickers provide opportunities for the recyclable market, generate income for the category, and guarantee service in hard to reach areas • Improvement of infrastructure, public roads and/or roads, technical capacity, qualification of the workforce • Investments in data collection technologies

Author/Year **GR**	**Weaknesses of urban solid waste management**	**Opportunities/suggestions for urban solid waste management**
Chen, Geng and Fugita, 2010 **3. CHINA** Asia	• Largest USW generator in the world • Informal agents are the largest collectors of recyclable materials • 2 million Chinese are involved in the collection of recyclables • USWM performance differentiated between municipalities • Inequality distribution of financial resources • Shortage of generation and gravimetry data • Absence of uniform standard for waste sampling and categorization • Inadequate sites for MSW incineration • Fragile local policies • Uncertainty in markets for recyclable or compostable products • Low demand for organic compost • Improper location of recycling centers • Lack of adequate resources and technologies in central regions • Landfills and incinerators are the most encouraged systems • The method of composting treatment is not widespread	• USW collection largely uncoupled from economic growth • Promulgated USW policy in 1996 with incorporations: (2001) incineration pollution control standard; (2002) commercialization of waste treatment, collection of waste treatment fee and promotion of industrialization (2004) extended producer responsibility (EPR); (2005) waste separation and collection systems; (2006), entitled “Environmental Protection Model Cities” and “Green Cities”, Promotion of Incineration and Composting, Requiring the Integrated Preparation of the USWM Plan; (2007) reduction of waste volume; (2008) fees for plastic bag use, landfill construction and operation regulations, (2009) Circular Economy • Availability of public and private resources as well as sources from international organizations • Encourage support from local governments • Improve information transparency • Growing support from international and private sector organizations
Kubanza and Simatele, 2016 **4. KINSHASA** Congo África	• Waste management • Poorer community does not receive services • Scarce resources • Poor institutional structure • Poor sanitary conditions • Precarious water supply20% to 40% of waste is collected • Collection is restricted to the richest neighborhoods • The supply of scrap bags and garbage cans is irregular • Insufficient labor • Waste disposal outside the trash • The perpetuation of the civil war • High levels of corruption • Low environmental awareness	• Incorporation of urban social justice issues in USWM actions • Serve poor neighborhoods • Establishment of stable political regimes • Establishment of effective legislation and governance systems • Extend USWM service priority in poorer neighborhoods • Make information available to the community • Encourage the community to participate in decision making • Establishment of Policies for the Promotion of Environmental Education

Table 3. (Continued)

Author/Year GR	Weaknesses of urban solid waste management	Opportunities/suggestions for urban solid waste management
Patel, Jain and Saxena, 2010 **5. MADHYA PRADESCH** Índia Ásia	• USWM is not a priority • Waste collected from community dumps is deposited in the periphery • Environment as an environmental impact factor is being ignored • Waste pickers work in dumps in poor and unhealthy conditions • 60% of the area receives collection services • Waste disposal methods are non-systematic and unscientific.	• Promulgation of "Municipal Waste Rules (Management and Handling), 2000" addressing all aspects of collection management, transportation, storage, recycling, disposal processing. • Focus on integrated management • Need for data collection • Need to implement the rules established in the year 2000
Campos and Zapata, 2014 **6. MANAGUA** Nicarágua Central America	• Collection takes place 3 days a week • 33% of households are not served by the collection • 40% of the city is informal settlements • Collection only includes main streets • Collection is irregular in irregular and hard to reach settlements • Waste should be taken to main streets • No incentive for cooperatives	• 50% reduction in annual costs with decentralized USMW • Incentive to support projects for the creation of cooperatives and micro enterprises • Performance of the Department of International Relations • Implementation of projects co-financed by international and local Non-governmental organizations aimed at collecting in informal settlements. • Waste transfer stations and waste picker cooperatives • The projects supported the informal services provided by local entrepreneurs by generating • Employment generation, and improvement of public health with projects • Subversion of traditional models by decentralized community-based proposal
Ghesla et al., 2018 **7. SÃO LEOLPOLDO** Brazil South America	• Absence of official packaging standard • Waste mixed and exposed on public roads • Obstruction of streams by accumulated waste • Collection of recyclables by informal waste pickers • Recyclable waste sorting done at collector's homes • Low Environmental Awareness • Difficult access for trucks • Low capacity of sorting unit for recyclables • Resale of recyclables through intermediaries reduces revenue from this market. • Absence of composting plant	• Investment in Environmental Education • Collection Division: recyclable collection (Collection A); collection of putrescible and non-recyclable organic waste (Collection B) and the collection made by the city's waste collectors (Collection C) • Occurrence of the selective collection (SC) program once a week • Participation of 65 people from outsourced companies as well as informal collectors in the collection of recyclables • SC achieves 100 points, including schools and agencies Companies that generate large volumes are responsible for transportation and the costs of depositing

Author/Year **GR**	**Weaknesses of urban solid waste management**	**Opportunities/suggestions for urban solid waste management**
	•	• 5 sorting units receive recyclable waste • Alliance between municipal administration and waste picker cooperative • 100 families work in the cooperative • Increase processing capacity of sorting units • Installation of Composting Plants • Formalization of informal waste pickers • Greater Encourage for Waste Pickers
Fernando, 2019 **8. SRI LANKA** Ásia	• Insufficient physical space for final disposal, composting and recycling • Vehicle insufficiency and modern technology • Poor regulatory structure, lack of skilled labor • Lack of community awareness • Waste disposal in open and low altitude areas • Lack of training of operators • Infrastructure and resources for waste collection and disposal are absent in most parts of the country • Dispersing and dumping without control of the residue in the environment • Government neglect due to financial difficulties • Demotivation and low esteem of waste sector employees • Skepticism about compost quality affects product marketing • Composting and recycling processes lack appropriate technology • Deficient existing regulatory instrument • Most local authorities do not have an adequate solid waste management program	• Existence of the National Waste Management Policy built on the "Polluter Pays Principle"; Citizen participation for successful implementation of USWM; Political support for the successful implementation of USWM plans providing for public-private participation • Encouraging attractive remuneration for employees in this sector; Encouraging the development of the compost market • Incentive to the elaboration of municipal plans of USWM • Need to acquire appropriate technologies to support recycling and composting businesses • Encouraging inclusion in the school curriculum of Waste Management • Need for strict rules and regulations to promote environmentally friendly behavior • Encourage the reduction of the use of polyethylene and plastics and increase the prices of shopping bags • Continuous Awareness Program

Table 3. (Continued)

Author/Year **GR**	**Weaknesses of urban solid waste management**	**Opportunities/suggestions for urban solid waste management**
Yukalang Clarke and Ross, 2018 **9. THA KHON YANG** Maha Sarakham (TKYMS) Thailand	• 60% of USW are collected • 2/3 of 60% of USW collected are landfilled • Deficiency in water supply, sanitation roads and utilities • Shortage of data related to USW generation • Absence of USW management adequacy programs • Absence of fixed points for waste collection. • Waste quantity exceeds the capacity of collection and transport trucks • Collection routes are incomplete • Waste collectors precariously separate • Waste separation initiatives were unsuccessful	• Local governments have autonomy to exercise solid waste management • No TKYSM pressed to fit USWM • Investment in transfer, recycling and composting stations • Investment in technologies • Investment in Environmental Education • Collection process reformulation • No deposit in dumps • Expansion of income source through waste treatment processes promoting the introduction of these new resources in USWM • Preparation of municipal instrument for sector regulation
Parrot et al., 2009 **10. YAOUNDÉ** Cameroon Africa	• Municipal managers do not prioritize USWM • Absence of clear legislation • Poor infrastructure • Scarce financial resources • 70% of roads are unpaved • Dumpsters that are difficult to access due to their distance from homes • 40% of waste is collected • No maintenance for vehicles • 5% of waste is recycled • 1/3 of people involved in recycling are under 15 • 7% of households are familiar with recycling • Dependence on ONG´s and associations for collecting • 75% of waste is organic in nature • Per capita generation is 0.6 kg in the dry season and 0.98 kg in the rainy season. • Rainy season is the worst collection service • Gap between generation and collection of USW • Collection inefficiency, low or non-existent in peri-urban neighborhoods • The final disposal system is dumps • Not enough equipment	• Build transfer stations • Install dumpsters • Encourage (technical, institutional and financial support) for Non-governmental organizations and Community Based Organizations (CBOs) • Develop research related to organic compound • Raise environmental awareness of managers, collection companies and the community • Develop strategic planning • Programs targeting heavily indebted poor countries (HIPC) or other international support agencies to promote improvements in USWM • Community encouragement to participate in recycling projects

Source: Prepared by the authors, 2020.

Table 4. (10 most recurrent weakness aspects of USWM)

GR	Legislation/Program Ineffective	Ineffective Collection	Absence Selective Collection	Absence Recycling	Absence Composting	Dump Deposit	Technology Ineffective Structure	Absence of Team Qualification	Informal Waste Pickers	Resources Scarce	Sum of aspects
1. Allahabad	X	X	X		X	X	X	X	X	X	8
2. Cairo	X	X	X	X	X	X	X	X	X	X	10
3. China		X				X	X	X	X	X	6
4. Kinshasa	X	X	X	X	X	X	X	X	X	X	10
6.M.Pradesch	X	X	X	X	X	X	X		X		8
5. Managua	X	X			X				X	X	5
7. S.Leopoldo					X		X		X	X	4
8. Sri Lanka	X	X	X			X	X	X	X	X	8
9.Tha K. Yang	X	X	X	X	X	X	X	X	X	X	10
10. Yaoundé	X	X	X	X	X	X	X	X	X	X	10
Recurrence of Aspects	8	9	7	5	8	8	9	7	10	9	-
Recurrence of Aspects in Geographic Regions											
% of Regions with the present aspect	80%	90%	70%	50%	80%	80%	90%	70%	100%	90%	-

Source: Prepared by the authors, 2020.

Table 5. (10 aspects considered as the most recurring opportunities of USWM)

GR	Appropriate Law Country	Selective collect	Recycling /Transfer Station	Compost	Sanitary landfill	Efficient collection	Government support	International support	Formal Pickers	Environmental Awareness	Sum of aspects
1. Allahabad	X										1
2. Cairo											0
3. China	X	X	X	X	X		X		X	X	8
4. Kinshasa											0
5. M. Pradesch	X										1
6. Managua	X	X	X		X		X	X	X	X	8
7. S. Leopoldo	X	X	X		X	X	X		X	X	8
8. Sri Lanka	X		X	X							3
9. Tha K Yang	X										1
10. Yaoundé								X			1
Recurrence of Aspects	7	3	4	2	3	1	3	2	3	3	-
Recurrence of Aspects in Geographic Regions											
% of Regions with the present aspect	70%	30%	40%	20%	30%	10%	30%	20%	30%	30%	-

Source: Prepared by the authors, 2020.

Table 6. Phases of debates on the evolution of the USWM and level of adhesion of the GR

Period	Main Actions/Focus of each phase Demajorovic (1995)	GR with partial consideration of priorities	Groups: Adhesion Level
1st phase 60's until the mid-70's	**Focus on final disposal in landfills** Prioritization of final waste disposal Disposal in most recent open dumps Waste disposal to landfills and incinerators	---	**Lower Adhesion** Surpassed phase 1 priorities
2nd phase Mid-1970s to the 1980s	**Focus on Recycling** Recovery and recycling goals Establishment of new relationships between end consumers and producers, and between distributors and consumers, to ensure the reuse of part of the waste Volume reduction for landfills and/or incinerators. Advantages from reuse (lower energy consumption; reduced waste volume)	MANAGUA SÃO LEOPOLDO	**Middle Adhesion** Surpassed Phases 1 and 2 Priorities
3rd phase Late 80's, 90's	**Focus on generation reduction and reuse** Greater focus on reducing the volume of waste since the beginning of the production process and at all stages of the production chain Reduction in consumer goods generation Prioritization of reuse over recycling Harnessing the energy present in waste prior to disposal in landfills and incineration processes	CHINA (not in its entirety)	**High Adhesion** Surpassed Phases 1, 2 and 3 Priorities

Source: Prepared by the authors, 2020.

The results of the analyses, related to the level of adherence to the priorities established in the phases of Demajorovic (1995), are shown in Table 6.

According to Table 6, only China can be classified as belonging to the high adhesion group, having overcome the priorities established in the 3 phases. The regions that surpassed the priorities established in phases 1 and 2 were São Leopoldo and Managua, and therefore, were classified in the medium adhesion group. The GR of Allahabad, Cairo, Kinshasa, Madhya Pradesch, Sri Lanka, Tha Khon Yang and Yaundé, were classified in the group of regions without any adherence to priorities established in the Demajorovic phases (1995), which means that they are still trying to solve problems prior to the first phase, such the collection or the proper final disposal of its waste.

CONCLUSION

The detailed study of the processes related to the waste sector is extremely important to map the level of evolution of the USWM in each geographic region. Our results may give support to managers and policymakers in decisions and in the development of projects and programs for the adequacy of waste management.

Although the paper is densely focused on developing countries, (middle or low- income countries), the USWM scenario of developed countries (high income countries) was also discussed. The latter being an important condition in order to visualize the differences of waste management practices between these countries. Although the burden of the waste sector responses is advanced for developing countries, it also falls on developed countries as they still face the great challenge of reducing generation rates as a consequence of economic progress and high consumption. High-income countries are responsible for 34% of the waste generated in the world (Kaza et al., 2018).

Through the synthesized analysis of the Geographic Regions, it was important to understand aspects related to the overcoming or not of the priorities established in the phases addressed by Demajorovic (1995). Furthermore, we sought to understand the characteristics of the profile of each group based on the classifications suggested by the (Kaza et al., 2018; Hoornweg, and Bhada-Tata, 2012 and UNDP, 2019). The results point to a disturbing scenario, since 70% of the analyzed regions were not able to overcome the priorities set, in phase 1 of Demajorovic (1995).

Thus, it can be said that 70% of the GR has approximately 60 years of delay in its models of USWM. It is important to reflect upon the factors that contribute to the unsophisticated scenario in the GR, such as the precarious political, financial, technological and educational structure. Some GRs, especially the poorest ones, still strive to solve problems related to basic individual needs, for example, water supply, energy supply, housing and food, making the waste agenda secondary. Nevertheless, some realities suggest that even with financial potential and managers being aware of the urgency of USWM adequacy, the waste sector is neglected to the detriment of investing in sectors that offer higher returns and higher visibility for policymakers.

Table 7. Characteristics of Groups

Groups: Adhesion Level	∑ GR	GR	Income*	Region Classification**	Country HDI ***	Score of Weaknesses or variation (Table 4)	Scoring Opportunities or variation (Table 5)
High Adhesion	1	China (not in its entirety)	Upper-Middle	East Asia and Pacific	China 0,761	6	8
Middle Adhesion	2	S. Leopoldo	Upper-Middle	Latin America and Caribbean	Brazil 0,765	4-5	8
		Managua			Nicaragua 0,660		
Low Adhesion	0	--	--	--	--	-	-
No Adhesion	7	Allahabad	Lower Middle	South Asia	India 0,645	8-10	0-3
		Cairo	Lower Middle	Middle East and North Africa	Egypt 0,707		
		Kinshasa	Lower Middle	Sub-Saharan Africa	Congo 0,480		
		M. Pradesch	Lower Middle	South Asia	India 0,645		
		Sri Lanka	Upper Middle	South Asia	Sri Lanka 0,782		
		Tha K. Yang	Upper Middle	East Asia and Pacific	Thailand 0,777		
		Yaoundé	Lower-Middle	Sub-Saharan Africa	Cameroon 0,563		

Source: Prepared by Authors, 2020.
* World Bank (2012); ** World Bank (2018); *** UNDP (2019).

It should be acknowledged that most of the assessed GRs are located in countries that have already passed their sustainability-appropriate legislation, such as India, Brazil, China and Sri Lanka. This fact shows flaws in the implementation of the legislation and suggests the need for scientific studies with this approach.

The analysis of adherence to the priorities established by Demajorovic (1995) was important to corroborate the results of the synthesized analyses of each GR, especially with regard to the sum of the opportunities and weaknesses of each region. The four groups proposed in this study had the following classification: High Adhesion (China), Medium Adhesion (São Leopoldo and Managua) and No Adhesion (Allahabad, Cairo, Kinshasa, Madhya Pradesch, Sri Lanka, Tha Khon Yang and Yaoundé). None of the regions were classified in the Low Adhesion group. Table 7 presents the characteristics of each group.

According to table 7, all low middle-income regions belong to the Non-Accession group. As stated by Kaza et al. (2018), low middle-income countries have the following rates: collection (51%), final disposal in landfills (18%), final disposal in dumpsites (66%), final disposal and recycling (6%), that is, they are countries with USWM models that are still far from the sustainability criteria. All regions classified in the Middle or High Accession groups are countries, or integrate countries, classified as upper middle income. World Bank data for upper middle-income countries are: collection (82%), disposal in landfills (54%), disposal in dumpsites (30%) and recycling (4%).

Even though China was classified in the High Adhesion group, this region has not yet been able to fully solve problems of collection, final disposal and reuse of its waste. Another important conclusion concerns the variation in the score of both aspects considered as weaknesses and opportunities. It is noted that the group with No Adherence to the priorities of Demajorovic (1995), varied from 8 to 10 points, for the aspects considered as weaknesses of the USWM. The Medium and High Adherence groups had positive results in relation to the aspects considered as opportunities for the USWM, reaching a total of 8 points and a variation of 4 to 6 points for the aspects considered as weaknesses of the USWM.

When considering both the regional classification and the performance of USWM, it is noticed that the members of the group of No Adherence to the priorities are located (3) in South Asia and (2) in Sub-Saharan Africa. These are locations with the worst performance in the world, both in terms of collection (44%) and final disposal in dumpsites (ranging from 69% to 75%), according to data from Kaza et al. (2018). The members of the High and Medium Accession groups are, or are part of, countries with approximate Human Development Indexes (HDI), with a range from 0.660 to 0.765. While the members of the No Adhesion group, have HDI ranging from 0.480 - 0.782. The results of the Sri Lanka region and Tha Khon Yang differ from the other members of the group, because even though they belong to high-middle income countries and have their HDI relatively higher than the members of their group; they scored 80% or more in aspects considered as weaknesses of USWM. The results of the municipality of Tha Khon Yang also differ in terms of location, since according to Kaza et al. (2018) the East Asian region has the third best average in terms of, for example, the treatment of its waste, second only to the regions of North America, Europe and Central Asia. The results point to a trend revealing that the middle-high income countries perform better in their USWM compared to the low-middle income countries. Another trend identified is that the GRs with the highest score for USWM opportunities integrate the regions of Latin America and the Caribbean and East Asia, with the exception of the municipality of Tha Khon Yang.

Thus, the discussion on the evolution of the debates on this theme should represent a driving force for the implementation of projects, programs and regulatory instruments that aim to minimize the impacts of waste accumulation, not losing sight of the fact that the implementation should be adequate to the different contexts of the countries, states and/or municipalities.

It is expected that this study will give a clearer contribution to the academic discussions related to the USWM models and will support municipalities, states and countries governments that are motivated in adapting their models.

The temporal factor is considered as a limitation of this study, as we considered the time when each scientific study was made for each GR. Since the time each study was made, it is possible that some aspects of USWM in GRs have changed. It is therefore suggested that further studies should be developed for possible updates.

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Chapter 6

WASTE PLASTIC RECYCLING: CURRENT STATE, CHALLENGES, AND FORTHCOMING OPPORTUNITIES IN RECYCLING TECHNOLOGY

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ABSTRACT

Plastics are low-cost, robust, and lightweight polymers of hydrocarbons, which can be easily converted into diverse products for a wide range of applications. These evident characteristics of plastics make them irreplaceable candidates for many applications including polymer industry, automobile industry, energy industry, aerospace industry, etc. However, such huge applicability of plastics made them excessively manufactured materials for the fulfillment of widespread necessities, due to this reason plastics are frequently available waste materials in the environment. Waste plastic causes several problems to the environment by polluting drinking water, polluting oceans, polluting atmospheric air, causing soil erosion, also acting as the inductive reason behind several deadly diseases including cancer. Waste plastic has several harmful effects on animals and human life, including direct effects on nature and related resources. Currently, plastics such as nylon, low-density polyethylene (LDPE), and high-density polyethylene (HDPE) are creating more challenges for the scientific community. However, these types of waste plastics can be converted into value-added products or in other forms of plastics, through recycling technology. The recycling ability of any material mainly depends on its capability to reacquire the properties of its original state. Various researchers have stated the management scheme for plastic waste (PW) and rectified the diverse applicability of

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recycling technology for the appropriate management of waste plastics. Since plastics are being recycled since the early 1970s, thus the quantity, quantity, and processing of the recycling approach have varied a lot from 1970 to 2020 the development of new degradation catalysts affected the recycling process tremendously. Incorporation of advanced technologies for the collection, segregation, and recycling of different waste plastics are opening bunches of opportunities, that can be useful with combined actions of municipality boards, industry, and governments, and can reduce the mainstream problems relating to waste plastic. However, to accomplish such an aim, recycling can act as a very significant technology, that not only delivers opportunities to reduce waste plastic but also produces value-added products such as carbon nanomaterials (CNMs), hard-soft carbon (HSC), oil, syngas, etc. In this chapter, we have briefly discussed recycling technology in past, present, and futuristic scenarios in context to waste management strategies. This chapter compiles the waste plastic recycling, and its current state, respective challenges, and forthcoming opportunities in recycling technology. Additionally, this chapter reviews the typical pyrolysis technologies and their excessive effects on waste plastic management.

Keywords: waste plastic, recycling technology, pyrolysis, carbon nanomaterials (CNMs)

1. Introduction

The existing situation of waste plastic (WP), and its inadequate management is a concern to the globe, due to excessive consumption and production of plastics. Different industries are using plastics for their growth, and manufacturing processes, like plastics, have become very essential and integral part of basic human needs. In the last few decades, the production, and consumption of plastics have enhanced globally with accelerating rates [1]. Usually, the plastics are non-biodegradable and can persist in the environment for a very long time [2]. Also, plastics are polymers that can agglomerate to form long-chain or branched-chain polymeric fragments that are made up of a combination of their numerous monomers. Over 92% of manufactured plastics are either thermoplastic i.e., plastics that can be melted at a certain temperature, or thermoset plastics i.e., plastics that cannot be melted [3]. Different physical and chemical properties of plastics for the most part depend on their building units i.e., monomers.

If the same monomer is the building block for the whole polymer it is called homopolymers, and if more than one monomer is involved in the synthesis of polymer it is called a copolymer. However, the universal presence of plastics has made them an integral part of the universe [4]. Although over 99% of the plastics are manufactured from resources like natural or synthetic oils, these plastics mainly include some chemicals, such as chlorine, phosphorus, and these chemical components are well known as the inducer to many diseases likewise cancer, respiratory problems, skin disease, etc., [5].

Also, the hazardous elemental composition present in trace amounts, along with the huge durability of plastic causes several issues to the environment such as soil erosion, air pollution, water pollutions, and landfill dumping, etc., [2-5]. Universally, 8.3 billion tonnes of plastics have been manufactured since the 1950s. However, 12% of which is incinerated, 9% is being recycled, and 79% is being dumped onto our surroundings [6].

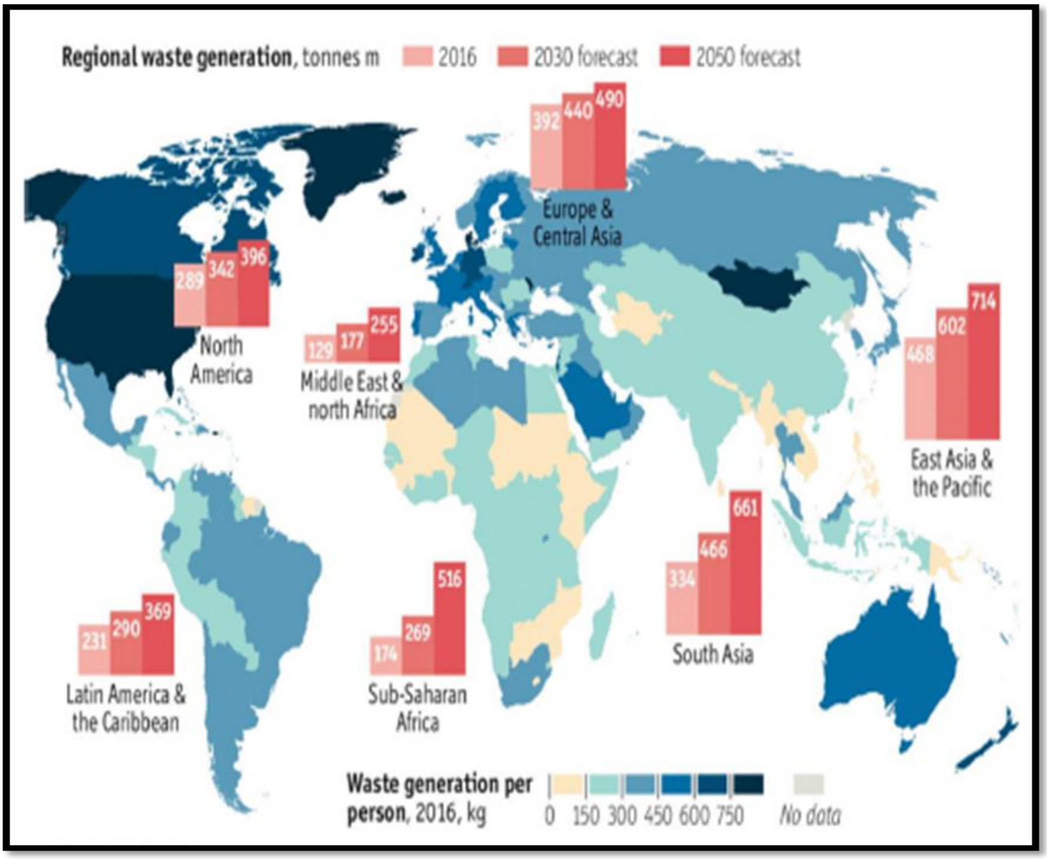

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Figure 1. Recent scenario of global waste projection (Source: Daily chart: Global waste generation will nearly double by 2050, The Economist, 2018).

Among different kinds of plastics, PVC is mostly used plastic for the manufacturing of window pipes, wiring pipes, floor covers, sheets over the roof, packaging materials, shopping bags, clothing, and building materials [7]. Thermal degradation of plastics can reduce their quality and the same can act as the crucial method to deal with WP. However, some donor solvents can ease the thermal degradation of WP, as the donation of hydrogen alters the overall production of hydrocarbon along with their dispersal [8].

Considering, overall consumption of WP, around 70% remains untreated in the environment, which results in 5.6 million tons per annum (TPA) WP production [9]. Different plastics such as polyvinylidene chloride (PVC), polypropylene (PP), polyethylene (PE) is some of the major contributors to the production of WP [10]. However, the consumption of plastics may vary depending upon their thermal and chemical stability [11]. More is the WP more will be the need of recycling the virgin WP. Plastics are also known as the most significant pollutant, in all of the waste materials including municipality waste, land waste, and ocean waste as most of the goods and tools of human need are manufactured using these plastics [12]. The harmful nature of plastics in terms of health and environmental problems is creating many issues and irregularities to the natural environment and also to the climatic conditions. WP emits methane (CH_4), and carbon dioxide (CO_2) on burning, these gases result in most of the greenhouse effect (GHE) to the environment. Recently one study revealed that the GHE caused by CH_4 gas is far more superior to CO_2 [13].

This can be visualized with the help of Figure 1, which shows the global scenario of waste distribution. The possible control over such enlargement of WP can only be controlled by using advanced pyrolysis technologies. Pyrolysis technology uses low to high temperature based thermal breakdown of plastics and results in the production of their monomeric units or smaller counterparts along with fuels and gases. However, various modern advancement has been done over the decade for converting waste plastics into value-added products using pyrolysis technology. Thus, the pyrolysis technology has acted as a pioneer in the field of waste management especially for WP management, by resulting in the synthesis of extensively value-added products such as carbon nanomaterials (CNMs). CNMs mainly include graphene, carbon nanotubes (CNTs) and quantum dots (QDs), etc. However, in CNMs, graphene has got most of the research attention due to its marvelous properties [12-16].

A few of these properties are extremely high tensile strength, high mechanical strength, excellent conductivity, light-weighted structure, and high surface area, etc.[17-18].Graphene can be synthesized using different recycling methods, using waste plastic and other carbonic materials as precursors. This chapter discusses WP recycling technologies in detail, along with the status of universal WP, its composition, and associated futuristic possibilities. A detailed discussion on types of WP, their production, associated hazards along different methodologies used for their demolition have been included. Different traditional and advanced pyrolysis approaches have been mentioned, along with the current status of recycling technology, approaching challenges, and imminent opportunities of waste management. We hope this chapter will refill the gap between different recycling technologies and will help in the visualization of ground reality.

2. Plastic Waste Management: Overview

The current state of waste plastic management is drastically complex worldwide. Over 90% of fresh plastic is produced through natural resources such as gases and oils. Petrochemical companies such as total, ExxonMobil, and Sinopec are synthesizing various plastics using naturally manufactured petrochemicals.

After manufacturing plastics, the petrochemical companies usually trade these plastic polymers to the manufacturing companies. Further, manufacturer companies make different objects and tools using these plastic-based polymers. For instance, a bottle of mineral water can be made using PET [19]. Management system for waste plastic has become quite complex from one country to another, as most of the plastic goods become waste after using them only for one time. Based on waste plastics distribution, economy and regulation these countries can be queued into the following groups.

- Developed countries that possess different recycling techniques to regulate their economy by developing novel recycling approaches for their waste management.
- Developed countries that are lacking recycling technologies for appropriate regulation of their economy and different waste management schemes.

- Developing countries having excellently developed industries for the treatment and development of new products from different waste materials.
- Developing countries that are lacking developed industries for the production of new products from different waste materials.

Many developed countries, mostly reliant on their local procedures for solid waste management. Such as, in Japan and Western Europe (WE), the waste management schemes with modest growth and advanced processes for solid waste management reported higher labor costs. The cost regulation of the recycling approach can have a variety of setups that can include a financing institution or organization, or industry, which can regulate the funding for the appropriate work that needs to be done under certain waste management schemes [19-21]. The financier organization usually involves as supplier, producer, or retailer of obtained goods. This approach is more suitable for the overall management of these waste recycling schemes also to the manufactured products and their pricing. Although, these recycling techniques are dependent on the type of plastic polymer, the infrastructure of industry, sorting of materials, also on the recycling and reusability of the products. These countries also use taxes to generate a good economy from traditional approaches, as they put taxes based on landfilling amount and incineration. These countries usually recycle up to 30% of their waste using these approaches. However, developed countries with non-regulatory approaches for solid waste management follow traditional approaches such as incineration and landfills. USA and Australia are included in this category having underdeveloped regulation of recycling techniques. These countries usually recycle less than 10% of their waste materials [18-20].

Waste management schemes in developing countries are mainly dependent on the related demands of the local population, economy, and infrastructural development. They do not follow any basic characterization approach and use the dumping approach at different illegal areas in an irregular way. The collection, segregation, and dumping are widely irregular in these countries. These cases are very usual in countries such as China, Brazil, and India where the processing is based on the volume of available waste materials, these countries usually recycle up to 20% of their waste materials. While, the developing countries had very few possibilities and limited industrial growth of recycling techniques tend to dump their waste materials into rivers, lakes, oceans, or anywhere near to the roads or fields. Plastic exists as a major component in municipality waste due to the excessive presence of discarded goods and packaging materials [22].

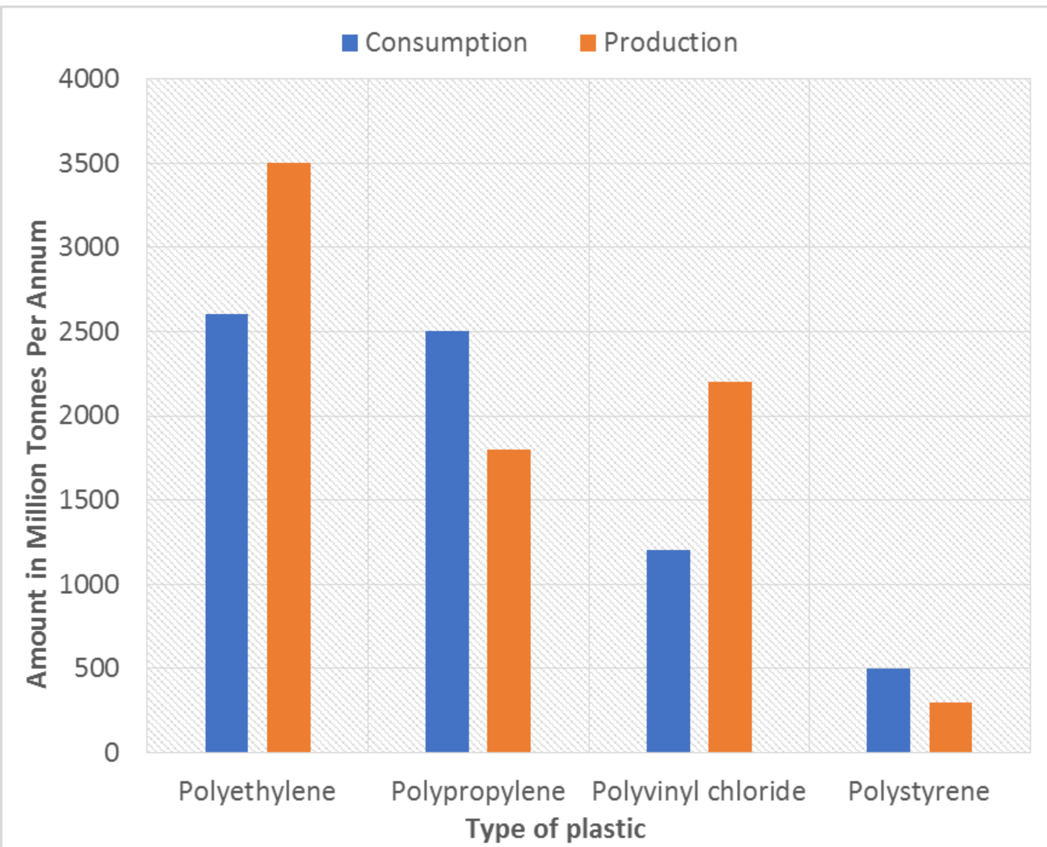
Nylon, high-density polyethylene (HDPE), and low-density polyethylene (LDPE) is the major raw component of waste plastic. The burning of plastic causes excessive problems to the environment and the earth. Carbon emission in the form of methane gas causes twenty-one times more global warming in comparison to carbon in the form of CO_2 [23].

Recently, various research groups are working on the recycling of waste plastic. According to the central pollution control board (CPCB), in Delhi, 90% of waste plastic is recyclable in India. Over 80% of this total waste plastic in India is dumped as a landfill, 8% is burned and only 7% is being recycled. Dumping of HDPE as a landfill is readily dangerous to the environment [24]. Plastic can also be used in wood composites as it acts as excellent blending material for different polymers and their composites. Similar work has been done by Deka et al., they have prepared a blended composite of wood plastic. Where they have done blending of PP, PVC, HDPE, and wood flour [25]. Obtained material composite can be used in any composite-based application.

2.1. Current State and Challenges

On a global scale, PW is the main contributor to universal solid waste production. Universally, the dumping of PW has become a huge problem due to their non-biodegradable nature and higher consumption worldwide [26]. Differences in the waste management approach worldwide are based on the economy of corresponding countries. As the countries with lower economies choose to follow incineration and landfills as the fruitful waste management scheme for the treatment of PW [27]. In Asia (Central and Eastern) around 93 million tonnes of the waste is being produced per annum, of which per capita production is around 0.29 to 2.1 kg/person/day [28].

As reflected in Figure 2, India has a deficit in plastics production and most of these plastics are imported to fulfill domestic needs million tonnes per annum (MTPA) [28-29]. Figure 1 is depicting the distribution of waste plastic in various regions of the globe [29]. According to U.S. Environmental Protection Agency (EPA), the packaging industry consumes alone 30% of total U.S.-based solid waste, which made the packaging industry the biggest contributor in consuming plastic-based materials [20-29].



Source: Govt. of India Statistics, Analysis by Tata Strategic.

Figure 2. Statistics on consumption and production of various plastic materials.

Such alarming situation of PW and emission of GHG on burning is causing the drastic changes in the climate of the globe [30]. However, the global expectancy in the demands related to plastic-related goods has made a quick rise in plastics production in the last few decades. Plastics, after entering into the ecosystem for once it can remain for decades or can stay for few centuries. According to a report on universal plastic waste generation by the year 2050, we humans will be producing about 26 billion tons of plastic waste each year [31-32]. Worldwide, Asia is the continent that contributes most significantly to WP production. China produces 0-0.49 kg per capita per day and India produces around 0.50 to 0.9 kg per capita per day [31-33].

The worst thing is its highest percentage ends up in the ocean worldwide. The unsustained management of WP around the globe is basically due to the use of traditional waste management models. Most of these models follow the "production → distribution → consumers → waste" model which leads to unsustainable management of WP. If the situation remains more or less similar, then expected waste generation reports are going to be true much quicker than their expectancy.

Indian continent region alone will contribute around 334 to 661 MT/day waste generation in comparison to 468 to 714 Mt./day from the Asia-pacific China region in between 2016 to 2050. Currently, globally 7 to 10 billion tonnes of waste increase each year which includes all kinds of wastes. According to the world bank, the situation of waste plastic and waste production is going to be the biggest challenge in front of the universe in the coming decade. On the economic point of view basis, the families with lower-income region earnings usually generate 0.09 to 0.60 kg waste per capita/day and the families in the lower-middle-income range produce about 0.16 to 0.79 kg per capita/day waste. However, the families with upper-income group produce the most waste of all categories, around 0.1 to 1.2 kg per capita/day [34-35]. Figure 3 is showing the waste production, MSW collection, land requirements for landfills, and population estimate in India by the year 2050.

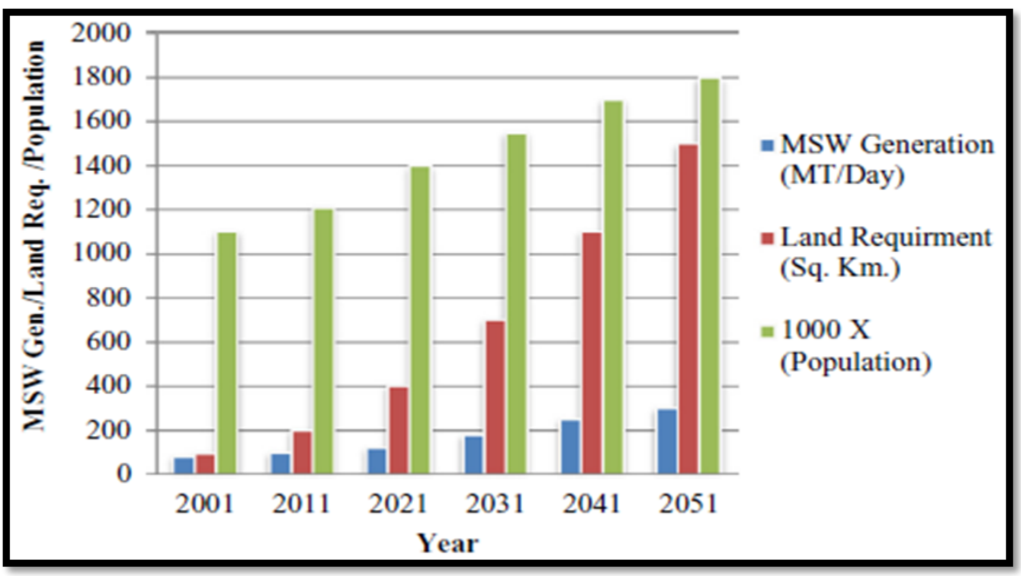


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Figure 3. MSW generation, land requirement, and population projection from 2001 to 2051.

The increment in the land requirement for the dumping and landfills of waste is a major concern with traditional techniques of waste management which are not only causing huge growth in the amount of waste but also causing several problems to the associated environment (Figure 3). The projected plot from 2001 to 2050 showing an almost 80% rise in the land requirements that are going to be drastic for India [35]. The same is visible for most of the developing countries along with few developed ones.

3. Recycling Techniques

Polymeric forms of hydrocarbons are called plastics, which can be breakdown into their native structural units via different methods such as chemical reaction, thermal breakdown, chemical vapor deposition (CVD), etc. However, for mass-scale production of these new products, waste plastics can be used as a precursor using different recycling techniques [36]. Recycling is a technique for the recovery of materials from WP, it may recover material with certain significant changes or without any changes in the original chemical form of the precursor. Recycling techniques are initially categorized by the International Standard Organization (ISO 15270:2008) into various types (Figure 4) [37]. These methods are briefly discussed in the section given below.

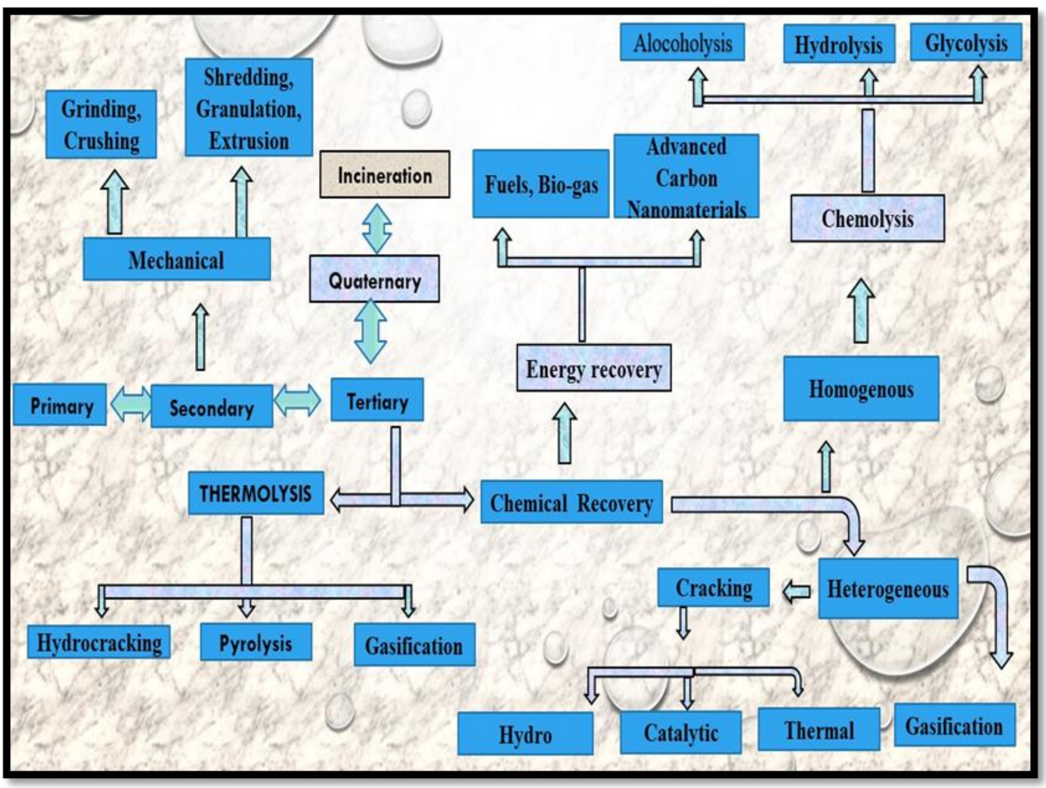

Figure 4. Types of recycling techniques.

3.1. Traditional Techniques

Primary and secondary recycling techniques are categorized as traditional techniques (Figure 4) mechanical recycling is well known as the traditional approach.

3.1.1. Mechanical Recycling

In the mechanical recycling (MR) technique, the WP gets recycled and then reused for different mechanical applications. MR is a very traditional and primary technique to recycle WP more often it was used in the early 1970s and was marketed on a broad scale. The major drawback with MR is its contamination, as the process moves to complexity contamination occurs at a severe rate [38]. The MR technique has been divided into two types i.e., closed-loop MR and open-loop MR technique. Closed-loop MR is a recycling approach having WP as a precursor for the synthesis of new products [35, 38]. WP gets mixed with fresh plastics and new products are made by mixing, usually, these products show equivalent characteristics as original materials. Sometimes, closed-loop MR is modified by different mechanical modeling such as grinding, crushing, and drying [39]. However, on other hand, open-loop MR technique different precursors are used and produce new products. Open-loop MR has different steps of recycling likewise categorization, chopping, granulation, and extrusion. These steps may be differently followed during the processor may be replicated during the processing [40]. Categorization of WP is done by knowing their chemical originality. Few techniques are used for the characterization of these materials using their chemical structure i.e., Fourier-transform infrared spectroscopy (FT-IR), electrostatic detection (ED), optical color detector (OCD) camera, etc.

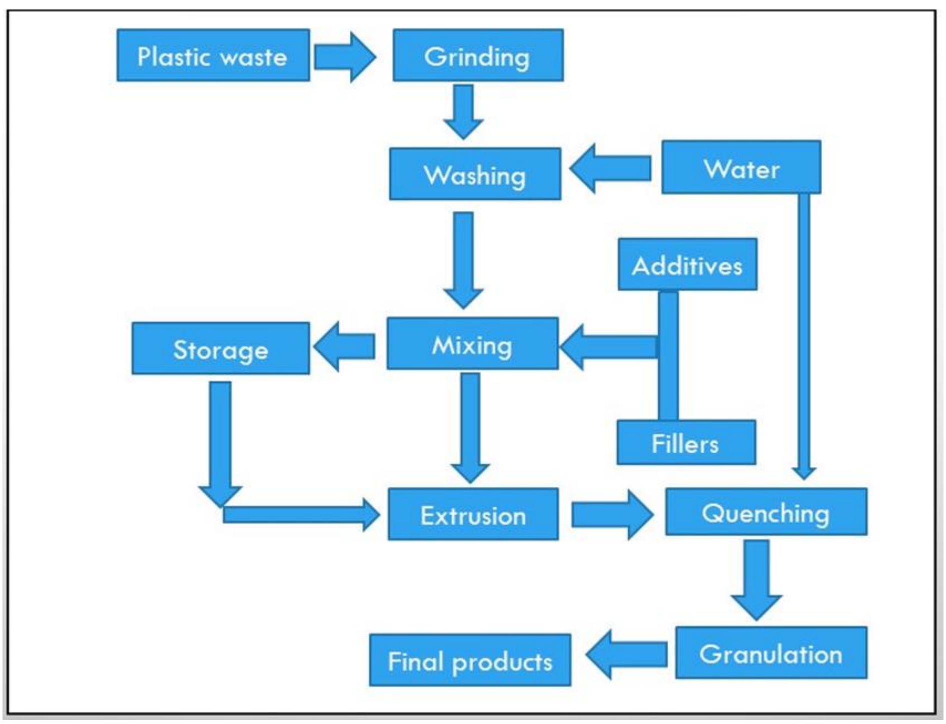

Figure 5. Steps of mechanical recycling approach.

However, OCD is a more popular technique that uses polymeric color and structure for their separation [39]. Sometimes, drying and washing can be used as the basic tool for the removal of contamination from WP, mostly these methods use caustic soda as cleaner [38]. Compounding is another technique that is used in MR, which uses the melting of multiple source materials along with WP. To obtain the desired product through compounding, different additives such as polymers, fillers, etc., are added with WP [40]. At final extrusion is used which mold the shape of material into the desired shape where die play a crucial role. Extrusion consists categorized into two headings one is single screw extrusion (SSE) and another one is double screw extrusion (DSE) [41]. Hoppers are used to feed the granules and the screw mixes the materials and acts as a heater [41-42].

3.2. Advanced Recycling Technology

Tertiary and quaternary recycling techniques are classified as modern techniques of recycling. Which includes thermolysis, chemical recovery, biological recycling, energy recovery, and incineration as the subdivision.

3.2.1. Biological Recycling

Biological recycling (BR) can only be used in some special kind of plastics. Initially, WP needs cleaning thoroughly before starting the biological procedure. BR is divided into two headings aerobic and anaerobic processes. Both processes depend on the microorganism-based decomposition of the plastic. However, aerobic decomposition requires oxygen, and anaerobic does not require oxygen for decomposition. According, to ISO only a few categories of WP, are approved that can be recycled through the biological recycling process i.e., ISO 17088, ASTM D 6400, ASTM D 6868, and EN 13432. However, the last product obtained through biological methods is compost (ISO 2008) [43].

3.2.2. Chemical and Thermal Recycling

In the chemical recycling (CR) technique chemical reagents are used for the degradation of waste plastics. The degradation products are usually carbonaceous products including gases and fuels as lower and higher hydrocarbons respectively. The CR technique is used for the production of fuels and chemicals from WP [39]. Reverse polymerization or de-polymerization is followed for the degradation of WP in monomers and other smaller units. Several chemical reaction pathways are followed during CR, which include alcoholysis, glycolysis, methanolysis, hydrolysis, esterification, thermolysis, etc, [41]. Methanolysis uses methanol as catalyst and solvents, while glycolysis uses liquid glycols as the solvents and catalysts [44].

Thermolysis is another CR approach where temperature-based thermal cracking of the WP is used for the production of fuels and gases. Pyrolysis, gasification, and hydrocracking are few other categories of thermolysis under CR [41]. Usually, the thermolysis process involves high-temperature degradation of the materials in the closed furnace. However, pyrolysis is processed under an inert atmosphere and certain pressure. The major products of such pyrolysis are carbonic solids, fuels, and gases. Though, the synthesis of these products mainly depends on the types of WP used during the process [40]**.** In the case of hydrocracking thermolysis, the necessary amount of hydrogen is introduced alongside rising temperature at a certain pressure in a closed furnace. While in the gasification approach the oxidative gases or their counterparts are processed into the furnace with continual thermal cracking [40].

3.2.3. Energy Recovery

Energy recovery (ER) produces different forms of energy using WP as the precursor, which includes electricity, heat, gases, and advanced carbon nanomaterials (CNMs) as the products. ER is a globally popular method for the production of advanced products. In Europe about 39.5% of WP recycled through [41]. Reproducibility of WP is the major reason behind WP being appreciable material for ER and especially for the production of gases, fuels, and other advanced products. Normally, the fuels produce 42.6 MJ/l and WP-based energy recovery produces 443.5 MJ/kg energy [40]. After discussing these techniques, it can be outlined that landfills and dumping are the two worst recycling treatments that can be done to WP. From the viewpoint, of these aspects of recycling technologies, the traditional methods such as landfill and dumping are completely restricted in few countries such as Switzerland, Finland, Norway, and Belgium.

4. Waste Plastic into Value-Added Products

WP due to the presence of good carbon content can be used as the source of various value-added products (VAP). The VAP is the products that can be prepared using ordinary material such as WP into drastically advanced products likewise carbon nanomaterials (CNMs), which can have good market value. Some examples of VAP that is obtained from WP are CNMs such as graphene carbon nanotubes (CNTs), different fuels and chemicals, etc. However, from the mass scale productivity and economically sustainable point of view, CNMs are the only better option to be synthesized from WP. Though, the bulk scale recycling of WP into advanced CNMs can only be possible by temperature, pressure, and catalytically controlled pyrolysis process [45].

Although various types of pyrolysis chambers can be used for such pyrolysis viz. moving and fixed bed reactor, tube furnace, muffle reactor, hydrothermal reactors, and crucible fixed reactors. Pyrolysis can be subdivided into two headings i.e., single-step process and stepwise process. The single-step process is involved with a single heating temperature and usually, it follows in situ approach, however, the stepwise process involves two or more steps of temperature-based parameters for the proceeding of precursor [46].

However, low-density and high-density plastics are converted into carbon nanotubes (CNTs), through single-step high-temperature catalytic pyrolysis [47]. Where the quantity of catalysts, the density of precursor plastics play a very crucial role along with the temperature and pressure of the furnace during pyrolysis. Polypropylene (PP) was used as the precursor by many researchers for the synthesis of MWCNTs through CVD. Briefly, the high-temperature range of furnaces i.e., 600˚C, 700˚C, and 800˚C were used under an inert atmosphere for 1 h using nickel as catalyst. The best quality of the CNT was obtained at 800 ℃. Synthesized CNTs had 85% transmittance of visible light at the wavelength of 550 nm, which is fairly good in comparison to 90% transmittance of traditional ITO-based films. These plastic-derived CNTs can be used as an active material for the fabrication of optical devices [48].

Jiang et al., reported the synthesis of CNTs using PP as a precursor. They have used Ni as the catalysts and carbenium ions as active intermediates. The carbenium ions were reported to control the thermal degradation of plastic. Several researchers have reported the transition metal-based catalysts with zeolites and organically modified montmorillonite (OMMT) or acids, capture the intermediate site of the carbonic cluster which causes the skeleton breakdown for carbonic molecules into smaller counterparts [46].

WP on degradation via chlorinated radical shows better aromaticity in the products and results in more production of CNMs [49]**.** Depending on the kind of catalysts the producibility can vary for these products such as CNMs from 5%-50%. Here, the type of precursor used along with catalyst, the temperature of the furnace, and pressure applied during the reaction are the main factors [50]. Single-step pyrolysis results in amorphous carbon along with CNTs. However, the production of these side products can be controlled by adjusting reaction parameters [50]. The presence of defects can also be controlled by optimizing these parameters**.** Multi stepped pyrolysis approach is a more scientific way to control the production of different CNMs along with secondary products. Mostly, the first step involves the degradation of WP into smaller hydrocarbons while the second step produces hydrocarbon as gases and fuels, and advanced CNMs [48].

Yang et al., reported a three-step pyrolysis approach using ferrocene as a sandwich in the primary reactor, further second unit decomposes WP into smaller hydrocarbons and finally, the third unit of the pyrolysis chamber produces CNTs [51]. They have reported the temperature around 120-140 ^{o}C as the sublimation temperature of ferrocene, the temperature around 450 ^{o}C for the degradation process of WP into smaller hydrocarbon units, and the high-temperature range of 800-850 ^{o}C for the formation of CNTs. These CNTs were reported to have 100 nm length, but they have not cleared the role of iron ions. It could be possible that they are used as degradation agents or for the CNT's growth. Liu et al., have reported a two-stage pyrolysis process for the degradation of PP into CNTs in a screw kiln reactor using HZSM-5 as the catalyst [52]. The product was mixed with Ni in a moving bed reactor and then they have reported hydrogen and CNTs as major outcomes. Maximum production of CNTs was reported at the optimized temperature of 700 ^{o}C and the maximum amount of hydrogen was produced at 750 ^{o}C temperature. Similarly, Wu et al., have outlined a two-step process for the production of CNMs from WP in presence of nitrogen at 500 ^{o}C [53]. Additionally, the second reactor was processed at 800 ^{o}C for the production of CNTs. They have worked on two catalysts for the production of CNTs i.e., Ni/Ca-Al and Ni/Zn-Al. However, graphene was synthesized using WP by Ruan et al., they have used the temperature of 1050 ^{o}C with continuous hydrogen and argon flow. Initially, they have used a CVD process where 10 mg of WP was placed in a Copper foil.

Now the quartz boat was placed at the temperature of 1050 ^{o}C for the next 15 min. They have used Argon at 500 cm^3 STP min^{-1} and hydrogen at 100 cm^3 STP min^{-1} with continuous flow. The furnace was placed at the pressure of 9.3 Torr and 1050 ^{o}C temperature, which was cooled so quickly to the normal room temperature. Additionally, the copper foil was melted by acids such as $CuSO_4$, HCl, and H_2SO_4 after using PMMA anisole solution (4%) which was coated on copper foil at 3000 rpm for 40 sec. Finally, continuous washing by distilled water was done until the solution become neutral [49-54].

Recently, Sandeep et al., have reported mass scale synthesis of graphene from WP using the pyrolysis process. Freshly, washed WP were chopped and then treated at the temperature of 400 ^{o}C inside a horizontal bed furnace where the presence of nanoclay acted as the degradation catalyst. The primary process was followed by high-temperature pyrolysis sat secondary reactor having a temperature of 750 °C in an inert atmosphere of nitrogen. The advanced spectroscopic techniques such as Raman, FT-IR spectroscopy, and microscopic techniques such as SEM and TEM imaging confirmed the materials as graphene [55].

CONCLUSION

There are different kinds of recycling approaches used for the decomposition and degradation of WP with or without synthesizing value-added products. This book chapter includes in-depth knowledge of different recycling approaches and products obtained from the recycling of WP. Detailed analysis on energy recovery, pyrolysis processes, biological recycling, and traditional recycling approaches has been done. To resolve all the issues related to the excess of WP, we require sustainable waste management schemes throughout the world. Impactfully it can be done by converting WP into advanced value-added products, which will short out environmental issues as well as it will boost the economy universally. Figure 6 illustrates an overall summation of all the options that can sustainably deal with WP and related issues. From environmental and economic aspects advanced multistep recycling emerges as a winner, which can not produce CNMs as advanced products but can also produce fuels, biogases, chemicals, compost.

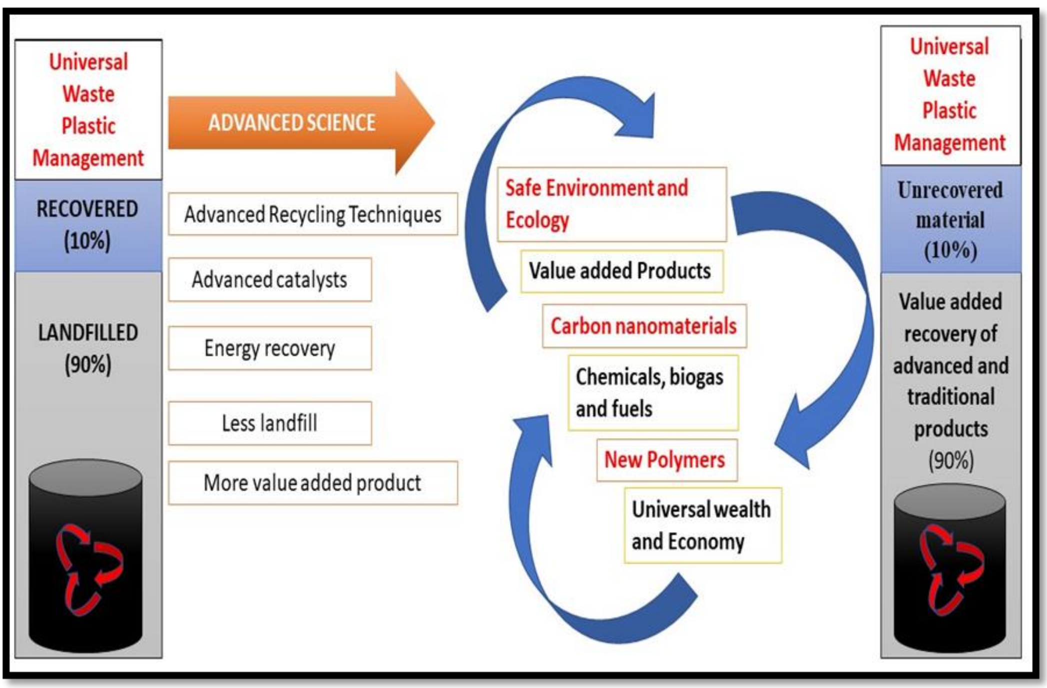

Figure 6. Futuristic and sustainable WP management approaches and possible aids.

Although there are lots of products obtained from multi-stepped pyrolysis, CNMs, fuels, and hydrogen have emerged as the most efficient ones. CNMs are universally acknowledged due to their extraordinary properties that are responsible for their universal applicability in different applications such as polymer composites, energy storage, energy conservation, water purification, drug delivery, etc. Thus, the use of WP as a precursor for the synthesis of different CNMs, hydrogen, fuels, and biogases will act as a valuable approach to reduce WP along with environmental glitches.

However, analysis, material recovery, economic aspects, and environmental benefits are the major concern related to recycling technology. If applied in developed and developing countries these recycling technologies can deliver good results with excellent sustainability. Though, from scientific, social, and market-based analysis following aspects can be followed before finalizing or referring the WP to any recycling industry.

- Certifying, the quality and types of WP, based on its ability of new products production and its availability as waste.
- The production cost of value-added products from WP and their original resource.
- Connections and distance between supply chain and producing industry.
- Total collection of waste plastic by municipality along with private and personal resources.
- Market value, energy recovery, response regulation, and possible environmental benefits around regional and international scale after processing material recovery through recycling approach.
- Possible hazards through the technology along with environmental benefits.

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Chapter 7

ENVIRONMENTALLY SUSTAINABLE WASTE MANAGEMENT AT A MAJOR GLOBAL HUB AIRPORT

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ABSTRACT

Sustainable waste management is increasingly being adopted by airports as a key part of their environmental sustainability strategies. Each year airports generate large quantities of wastes, which include both hazardous and non-hazardous wastes, all of which require careful handling to minimise their adverse impact on the environment. This study uses annual wastes data from 2008 to 2017 to examine how Frankfurt Airport, a major global air transport hub, manages its general (non-hazardous) and hazardous (toxic) wastes. Findings indicate that throughout the study period, Frankfurt Airport principal waste management strategy was the reclamation of wastes for recycling wherever possible. This is evident in the annual total wastes recoverability rate increasing from 83% in 2008 to 90.3% in 2017. Wastes that cannot be recycled are separated out and reusable materials are recycled or transported to regional waste-to-energy plants. Electricity and district heating are extracted from the energy that is produced from the incineration process. Hazardous wastes are collected separately, and such wastes are channelled away for recycling as far as possible. Where recycling is not possible, hazardous wastes are disposed of in approved incineration or in physical and chemical treatment plants. An important finding of the study is that the number of passengers using Frankfurt Airport throughout the study period increased significantly. Despite this strong growth in passenger traffic, Frankfurt Airport was able to reduce the waste per enplaned passenger from 0.45 kgs in 2008 to 0.32 kgs in 2017. A similar trend was found in relation to the waste per workload unit (WLU) which decreased from 0.34 kgs per WLU in 2008 to 0.24 kgs per WLU in 2017. The annual waste per aircraft movement also decreased over the study period from 49.63 kgs per aircraft movement in 2008 to 42.81 kgs per aircraft movement in 2017. Importantly, no wastes are disposed to landfill by the airport, as this waste disposal method has adverse impacts on the environment.

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1. INTRODUCTION

Airports are one of the principal actors in the global air transport industry value chain. Airports provide the critical infrastructure that is necessary to facilitate the movement of passengers and air freight consignments to their final destinations. The airport precinct is often home to air traffic control services, air cargo terminals, aircraft maintenance bases, flight catering firms, ground handling agents, hotels, logistics service providers, as well as ground service equipment (GSE) and government agencies. Every airport must manage the waste that is produced within its precinct and should aim to implement efficient and cost-effective waste management practices. Indeed, there are a wide range of sustainable practices that can make the management of waste at airports more economic and favourable on the environment. Importantly, successful airport waste management implementation offers the potential for an airport to positively impact the airport authority itself, customers, and the surrounding community at large (International Civil Aviation Organization 2020). Airports are the physical embodiment of the air transport sector, and consequently, they are the focus for many of the socio-economic benefits the industry delivers throughout the world (Paling and Thomas 2018). However, airport operations have adverse environmental impacts (Dimitriou, Vosaki and Sartzetaki 2014; Kumar, Aswin and Gupta 2020; Sameh and Scavuzzi sos Santos 2018), the significance of which is rising, and the trend that is regarded as being unsustainable (Thomas and Hooper 2013). As a result, the global airport sector is increasingly confronting similar challenges to other sectors of the economy in mitigating or compensating for these adverse environmental impacts in the context of limited global resources and the more restrictive environmental constraints (Paling and Thomas 2018).

A key environmental concern for airports is the annual generation of wastes that need to be handled in an environmentally sustainable manner. Airports produce large volumes of waste (Budd 2017; Dimitriou and Voskaki 2011; Edwards 2005; Pitt and Smith 2003a), and thus, sustainable waste management plans and "eco-friendly" policies are now being implemented at airports located throughout the world in an attempt for airports to become more environmentally friendly (Mehta 2015; Oto, Cobanoglu and Geray 2012; Vanker, Enneveer and Mäsak 2013). Airports generate both general (non-hazardous wastes) (Baxter, Srisaeng and Wild 2018a) and hazardous (toxic) wastes (Gössling 2018; McGormley et al., 2011). El-Din M. Saleh (2016, p. 4) has noted that "hazardous wastes are classified as hazardous if they exhibit one or more of ignitability, corrosivity, reactivity, or toxicity". These hazardous wastes can pose a threat to human health and to the environment if they are not handled in a safe way (Hooper, Heath and Maughan 2003). Airport can be broadly categorised as liquid or solid waste. Airport wastes can be further divided into non-industrial and industrial wastes (Janić 2011). Furthermore, even the quite benign solid waste stream has important environmental consequences arising from the requirement for waste disposal routes, such as incineration or by disposal to landfill (Hooper, Heath and Maughan 2003).

Waste management is defined as the management of waste materials, which are typically based on the management of wastes throughout all stages (production, handling, processing, storage, transport, and ultimate disposal) in such a way as to minimize human health risks, as well as avoiding the risks for animals and the environment (Park and Allaby 2013).

The objective of sustainable waste management is for the airport to minimize the amount of waste produced in the first place. Airports should acknowledge that waste materials, if properly segregated, can be valuable resources. Indeed, these resources can deliver both significant financial returns as well as environmental benefits for the airport (Thomas and Hooper 2013).

This chapter examines how Frankfurt Airport, a major global air transport hub, sustainably manage its wastes and thereby mitigates any adverse impact on the environment. Like other airports, Frankfurt Airport has both non-hazardous (general) and hazardous (toxic) wastes. The study examines the policies and measures that have underpinned Frankfurt Airport's sustainable waste management over the period 2008 to 2017. In addition, the study explores the importance of recycling of wastes as a key environmental sustainability measure by Frankfurt Airport. The first part of the chapter presents an overview of the sustainable airport waste management, the circular economy and waste minimization, as well as the waste management hierarchy, and waste management regulatory frameworks. This is followed by the research methodology that underpinned the study's case study. The chapter then examines Frankfurt Airport's environmentally sustainable waste management. The final section provides the conclusions of the chapter.

2. BACKGROUND

2.1. Sustainable Airport Waste Management

As previously noted, waste management at airports consists of both solid and hazardous waste (Baxter, Srisaeng and Wild 2018a; Janić 2011; McGormley et al., 2011). Together with the waste generated from aircraft, solid waste is also produced in airline offices, airport concessions (for example, restaurants, shops), flight catering centres, aircraft maintenance areas, landscaping, construction, and demolition activities (Chandrappa and Das 2012). Airports as well as airlines also generate substantial quantities of wastes from engineering and terminal facilities (Hooper, Heath and Maughan 2003). Hazardous waste may be present at an airport due to aircraft fuelling, aircraft maintenance (if conducted at the airport), rental car maintenance (waste oils), emergency generators, and may come from other activities. In addition, hazardous waste may be present at the airport because of past activities that have contaminated soil or water or because hazardous waste is being transported by aircraft or vehicle onto airport property (Culberson 2011).

Airport non-industrial wastes come from flight catering services that are provided onboard aircraft, and from the consumption of food and drinks by airport employees and visitors (cans, newspapers, food, and paper) to the airport. Industrial wastes originate from the daily activities associated with washing and cleaning aircraft and other ground service equipment (GSE), aircraft and engine maintenance, repair, and testing (which includes painting and metal work), aircraft de-icing, as well as maintenance of ground vehicles. These wastes comprise both hazardous and non-hazardous wastes (Janić 2011).

Table 1. Key airport landside stakeholders and typical types of waste generated

Airport Stakeholder	Types of Waste Generated
Airport Authority	Food, paper, plastic (in many forms), aluminum cans, restaurant and cafeteria grease and oil, electronics. Light bulbs, green waste from lawn cutting and landscaping, general rubbish, airport construction waste – concrete, asphalt, building materials, wood, soil, construction equipment waste, regular rubbish items.
Airlines	Food and drink containers, newspapers and magazines, food waste (from lounges/cafeterias), light bulbs, printer toner, paper, documents, and computer print outs.
Airport Concessionaires & Shops	Food, general rubbish, paper, toner cartridges, batteries, light bulbs, plastic bottles, aluminum cans, packaging.
Airport Hotel	Food waste, paper, rags/cloth, light bulbs, napkins, packaging materials, newspapers, green waste from lawn/plant care and landscaping.
Car Parks	Food waste, wastepaper
Cargo Terminal Operators	Tyres, fluids, lights bulbs, batteries, wood and wooden pallets, plastic wrapping material, green waste from lawn/garden care and landscaping, paper, computer printouts.
Air Freight Forwarders	Paper, toner cartridges, batteries, light bulbs, plastic, packaging, aluminum cans and plastic bottles, food, and general rubbish.
Government Agencies	Paper, toner cartridges, batteries, electronics, plastic bottles, aluminum cans, food, general rubbish.
Ground Handling Agent	Paper, toner cartridges, lights bulbs, batteries, plastic, aluminum cans, food, and general rubbish.
Ground Transport Interchange	Food waste, wastepaper, rags/cloth, newspapers, magazines, green waste from lawn care and landscaping
Passengers, Meeters & Greeters	Food, aluminum cans, plastic bottles, packaging, newspapers, magazines.
Railway Station	Food waste, rag/cloth, newspapers, magazines, wastepaper, plastic bottles, metal drink cans
Rental Car Firms	Paper, computer printouts, toner cartridges, batteries, light bulbs, oils and greases, aluminum cans, general rubbish.
Restaurants	Retail and food and beverage waste, cardboard boxes, paper, plastic items, packaging, food packaging, food wrappers, oils and grease, aluminum cans, plastic bottles, plastic, and glass containers.
Taxis Holding Bays	Food waste, wastepaper, rags/cloth, green waste from lawn care and landscaping

Source: adapted from Baxter, Srisaeng and Wild (2018: 3); London Stansted Airport (2010); Federal Aviation Administration (2013).

The waste generated at airports can be broadly divided into the waste generated by the landside activities undertaken at the airport as well as the waste produced by the key stakeholders involved in the provision of the airport's airside area operations. Landside means those parts of an airport as well as the adjacent terrain and buildings or portions thereof that are not in the airside precinct. The airside means the movement area at an airport, adjacent terrain and buildings/infrastructure, or portions, the access to which is restricted (Rossi Dal Pozzo 2015). Table 1 summarises the various types of wastes that are generated by the key stakeholders involved in the facilitation and handling of passengers and air cargo (where applicable) on the landside of an airport.

Table 2 shows the actors involved with the provision of passenger and aircraft-related functions on the airside of an airport and the types of waste generated from these operations. In addition to the passenger and aircraft-related waste, wastes are also generated from offices and from the concessionaires, for example, duty free shops and restaurants) operating at the airport.

Table 2. Key airport airside stakeholders and typical types of waste generated

Airport Stakeholder	Types of Waste Generated
Airport Authority	Food, paper, plastic (in many forms), aluminum cans, restaurant and cafeteria grease and oil, electronics. Light bulbs, green waste from lawn cutting and landscaping, general rubbish, airport construction waste – concrete, asphalt, building materials, wood, soil, construction equipment waste, regular rubbish items.
Aircraft Maintenance Firms	Food, packaging, oils, greases, solvents, packaging, wooden pallets, general rubbish.
Airport Concessionaires & Shops	Food, general rubbish, paper, toner cartridges, batteries, light bulbs, plastic bottles, aluminum cans, packaging.
Airport Fuel Farm &Suppliers	Paper, toner cartridges, batteries, light bulbs, plastic bottles, aluminum cans, food and general rubbish, oils, and grease from vehicles.
Air Traffic Control (ATC)	Paper, toner cartridges, computer printouts, light bulbs, batteries, food and general waste, oils, and greases from vehicles.
Airlines	Food and drink containers, newspapers and magazines, food waste (from lounges/cafeterias), light bulbs, printer toner, paper, documents, and computer print outs, oils and greases from ground service equipment and vehicles.
Cargo Terminal Operators	Tyres, fluids, lights bulbs, batteries, wood and wooden pallets, plastic wrapping material, green waste from lawn/garden care and landscaping, paper, computer printouts.
Fixed Base Operator (FBO)	Paper, toner cartridges, lights bulbs, batteries, plastic, aluminum cans, food and general rubbish, oils, and greases from ground handling equipment.
Flight Catering Centres	Food and beverage waste, cardboard boxes, paper, plastic items, packaging, food packaging, food wrappers, oils and grease, aluminum cans, plastic bottles, plastic, and glass containers
General Aviation/ Business Jet Centre	Paper, toner cartridges, batteries, electronics, plastic bottles, aluminum cans, food, general rubbish, oils, and grease from equipment maintenance.
Government Agencies	Paper, toner cartridges, batteries, electronics, plastic bottles, aluminum cans, food, general rubbish.
Ground Equipment Maintenance Firms	Paper, toner cartridges, light bulbs, plastic bottles and Aluminum cans, packaging, wooden pallets, oils and greases.
Ground Handling Agent	Paper, toner cartridges, lights bulbs, batteries, plastic, aluminum cans, food and general rubbish, oils, and greases from ground handling equipment.
Ground Transport Interchange	Food waste, wastepaper, rags/cloth, newspapers, magazines, green waste from lawn care and landscaping
Passengers	Food, aluminum cans, plastic bottles, packaging, newspapers, magazines.
Restaurants	Retail and food and beverage waste, cardboard boxes, paper, plastic items, packaging, food packaging, food wrappers, oils and grease, aluminum cans, plastic bottles, plastic, and glass containers.

Source: adapted from Baxter, Srisaeng and Wild (2018: 3); London Stansted Airport (2010); Federal Aviation Administration (2013).

The three key waste disposal options available to airports are:

1. Recycling: with this option the waste fraction is re-used again to produce raw materials that can be used for making new products or new forms of energy (Spilsbury 2010). The types of waste that can be recycled include paper, cardboard, glass, plastics, and metal.
2. Incineration: with this option, the waste fraction is incinerated. An option is for the waste to be incinerated in a Combined Heat Power plant (CHP) that produces heat and/or electricity (McDougall et al., 2007; Scragg 2009); and
3. Landfill: wastes that cannot be recycled or disposed through incineration may be disposed to landfill (Hauser 2009; McLaughlin and McDaniel 2012; Westlake 2014).

There are several environmental concerns related to solid waste produced at an airport. Firstly, the amount of waste generated at the airport is of considerable concern due to its potential impact on the environment. Secondly, the amount of waste which requires disposal by landfills is a further environmental concern (Culberson 2011). This is because the disposal by landfill is regarded as the least preferred option for waste management (Cossu and Stegmann 2018; Kien 2019; Pitt and Smith 2003b). A final environmental concern for airports is the location of the landfills in relation to airport runways and flight paths (Culberson 2011).

2.2. The Circular Economy and Waste Minimization

The circular economy is an economic system that is based upon business models that replace the “end-of-life” concept with reducing or alternatively reusing, recycling, and recovering materials during the production, distribution, and consumption processes of a firm (Ginga et al., 2020). The circular economy extends beyond recycling and is based upon a restorative industrial system that focuses on the treatment of waste as a resource (Ghosh 2020). Furthermore, the objective of the circular economy is to transform the economy into a circular operating system that improves resource efficiency, and involves resource recovery and re-use (Jurgilevich et al., 2016; Kubule et al., 2019; Mohammadi, Jämsä-Jounela and Harjunkoski 2019). Accordingly, the circular economy consists of three primary activities: the reduction in the use of virgin raw materials, the re-use of already processed materials, and the recycling of waste. In some instances, there is a fourth circular economy activity, that of the redesign of products (Burneo, Cansino and Yñiguez 2020; Kyriakopoulos et al., 2019). For a firm to achieve the benefits of a circular economy approach, the following steps need to be undertaken reuse, recycling, recovery, and waste prevention (Kyriakopoulos et al., 2019).

2.3. Waste Management Hierarchy

The waste management hierarchy underpins many businesses waste management and the hierarchy rank the waste disposal methods available to a firm from the most to least desirable in terms of their environmental efficiency (Davies 2016; Pitt and Smith 2003b). The waste management hierarchy is based upon firm’s resource allocation considerations. With such an approach, products should be produced sparingly or not all. At the expiration of their useful life, products and materials should be recycled into other useful goods wherever possible (McLaughlin and McDaniel 2012).

The waste management hierarchy seeks to minimize the generation of wastes in the first instance, optimize the opportunities for reuse and recycling of materials, and minimise the quantities of wastes that are disposed to landfill (Thomas and Hooper 2013). The waste management hierarchy is comprised of six levels: prevention of wastes, minimization of wastes, the reuse of wastes, the recycling of wastes, the recovery of wastes, and the disposal of wastes (Figure 1) (Baxter, Srisaeng and Wild 2018b; Davies 2016;). Waste avoidance refers to the measures that need to be implemented prior to a substance becoming waste (International Civil Aviation Organization 2020). In an ideal situation, waste would be avoided. This means that in the waste management hierarchy, reducing or preventing waste should be the principal goal of the firm. A firm can reduce its wastes by implementing two key strategies. The first strategy involves the firm reducing the volume of waste generated and disposed to landfills. In following this strategy, the firm reduces the impact of wastes on the environment. This waste handling strategy also reduces the harmful emissions generated from the wastes disposed in landfills. A further benefit is that it offers the firm energy and natural resources savings (Zhu et al., 2008). The second strategy involves the firm adopting an effective system to manage all unavoidable waste (Baxter, Srisaeng and Wild 2018b). A reduction in wastes can contribute to airport sustainability whilst also delivering cost savings. Waste reduction efforts may include the more economical use of materials. Alternatively, some wastes may be diverted to another process such as recycling. The processing of waste requires effort by the firm and consumes energy, but by extension, any activity that may contribute to reducing the amounts of waste also decreases transportation emissions and the energy necessary to process such wastes (International Civil Aviation Organization 2020).

According to the waste management hierarchy, re-use and recycling are the optimum methods of dealing with unavoidable waste (Baxter, Srisaeng and Wild 2018b; Pitt and Smith 2003b). Re-using waste, wherever possible, is preferable to recycling because the waste items do not need to be processed prior to their subsequent re-use (Güren 2015). Reuse occurs when something that has already achieved its original function is subsequently used again for another purpose (Zhu et al., 2008). Airports may reuse and repurpose materials. This can be achieved through contractual requirements with tenants to require waste minimization activities, for instance, the use of specific materials, cleaners, or paints. The reuse or repurposing of recovered materials also has the advantage of reducing the demand for new materials (International Civil Aviation Organization 2020).

The recycling of wastes involves the reprocessing of used materials that would otherwise be considered as waste (Zhu et al., 2008). Furthermore, the recycling of wastes involves the collection, sorting, processing, and their conversion into raw materials that can be used in the production of new products (Park and Allaby 2013). Airport wastes typically contains a large proportion of substances and raw materials which should be sorted and recycled (Kazda, Caves and Kamenický 2015). Recovery principally relates to the recovery of energy that is recovered from waste (Zhu et al., 2008). Waste that cannot be reused or recycled can be incinerated to generate heat or electricity (Makarichi, Jutidamrongphan and Techato 2018; Waters 2020; Zhu et al., 2008). Energy recovery processes include combustion, gasification, pyrolysis, and anaerobic digestion (Rahman, Pudasainee and Gupta 2017). In association with prevention and recycling measures, waste-to-energy (WTE) facilities can make a substantial contribution to a firm reaching the goals of waste management. Sophisticated air pollution control (APC) devices now ensure that emissions produced at waste-to-energy (WTE) facilities are environmentally safe. Incinerators provide the complete destruction of hazardous organic materials. Incineration also reduces the risks arising from pathogenic microorganisms and viruses, as well as for concentrating valuable and toxic metals in certain fractions. Furthermore, bottom ash and Air Pollution Control (APC) residues have now been turned into new sources of secondary metals. Consequently, incineration has become a materials recycling facility, as well (Brunner and Rechberger 2015). Thus, following recycling, the next best waste disposal route is incineration, which as previously noted, can also be used as a means of generating energy (Kaštánek et al., 2020). It is important to note, however, that there may be some undesirable environmental effects associated with waste disposal through incineration. Incinerated wastes require energy to be burnt in the incineration process.

Furthermore, the emissions and the ash resulting from incineration are potentially very dangerous. If not properly controlled, they can cause air pollution, which may have dangerous effects on human health (Lew 2021). Finally, disposal in landfill sites is regarded as the least desirable option in the waste management hierarchy (Manahan 2011; Pitt and Smith 2003b). Ultimately, such to regulatory requirements, some airport waste may be disposed to landfill. Whilst the waste management decisions such as reducing and reusing materials have the objective of waste minimization and recapturing materials and energy, there may be cases where this is not feasible. In some instances, disposal to landfill or alternatively by incineration is often the method of disposal for airport waste that cannot be processed in other ways (International Civil Aviation Organization 2020). In some instances, the landfill utilities themselves are engaged in the process of 'waste-to-energy' recapture through incineration or through other processes.

Figure 1. Waste management hierarchy.

The goal of airport operators should be to prevent the creation of waste at source, for example, through the bulk purchasing of materials to minimise packaging waste. Where waste generation is unavoidable at the airport, the reuse, recycling, or recovery of energy from waste is preferable to waste disposal. Objectives and targets for waste management can be agreed between the airport operator and their related stakeholders. The integrated nature of air transport operations, as well as the large number of stakeholders involved in the provision of air transport-related services, means that it is important that environmental management systems receive full buy-in from all the parties involved in the process. This should include mechanisms for the effective communication and collaborative decision-making established from the outset from the arrangements (Budd 2017).

An efficient and effective airport waste management system involves the sortation of waste at collection locations, that is, sorting the source into solid and liquid, non-hazardous and hazardous, waste, reducing waste quantities, ensuring the continuous improvement in reuse, recycling and reprocessing of waste materials, and permanent improvements in waste management practices (Janić 2011).

2.4. Waste Management Regulatory Frameworks

Airports are typically local entities. Consequently, waste management at airports is normally reliant on national and local regulation, drivers, and realities (International Civil Aviation Organization 2020). Indeed, throughout the world there are many countries that have legislated how airports should deal with waste and materials. These regulations and legislation typically define how airport wastes should be stored, collected, treated, or disposed of. Furthermore, airports are often confronted with specific operating restrictions due to the nature of the air transport business. For example, airports may be required to incinerate or arrange the transfer to a controlled landfill site for all "international" food waste from aircraft (Graham 2014). Thus, a municipality with waste reduction targets can have a direct influence an airport operator's waste management policy. In addition, stakeholder's arrangements with the airport operator also vary from location to location (for example, contracts, responsibilities) and this in turn may impact the ability of the airport operator to influence its stakeholders (International Civil Aviation Organization 2020).

The waste management regulations applicable for airports may vary between countries and, in some instances, between states in the same country, they do possess some common features that relate to:

- The handling of "special" wastes that are harmful to both humans and the environment or have been transported across national borders. Such wastes may consist of chemicals, clinical and radioactive wastes, and foodstuffs.
- Prioritizing waste minimisation to achieve reductions of waste in the first instance, before other waste management options are considered; and
- The requirement to promote the reuse and recycling of materials and discourage the disposals to landfill sites (Thomas and Hooper 2013, 565).

Hazardous or toxic wastes are managed very carefully in accordance with strict national and airport regulations governing collection, treatment, storage, and disposal (Federal Aviation Administration 2008; Janić 2011).

3. Research Methodology

3.1. Research Approach

The study's qualitative analysis was based on a longitudinal case study design (Derrington 2019; Hassett and Paavilainen-Mäntymäki 2013; Neale 2019). The principal advantage associated with the use of a qualitative longitudinal research design is that it reveals change and growth in an outcome over time (Kalaian and Kasim 2008). When undertaking case study research, the researcher's role is to expand and generalize theories (analytical generalization) and not to enumerate frequencies (statistical generalization) (Yin 2009). According to Baxter and Jack (2008, 544), a "qualitative case study is an approach to research that facilitates exploration of a phenomenon within its context using a variety of data sources". A case study allows for the exploration of complex phenomena (Cua and Garrett 2009; Remenyi et al., 2010; Yin 2018). Case studies also enable the collection of rich, explanatory information (Ang 2014; Mentzer and Flint 1997). This approach also permits researchers to build theory and connect with practice (McCutchen and Meredith 1993; Simons 2009).

3.2. Data Collection

The study's data was obtained from Fraport AG's annual abridged environmental statements. Qualitative data was also gathered from Fraport AG's web sites. Thus, in this study secondary data was used to investigate the research problem. The three guiding principles of data collection in case study research were followed in this study, that is, the use of multiple sources of case evidence, creation of a database on the subject, and the establishment of a chain of evidence (Yin 2018).

3.3. Data Analysis

The empirical data collected for the case studies was examined using document analysis. According to Altheide and Schneider (2013, 5), document analysis "refers to an integrated and conceptually informed method, procedure, and technique for locating, identifying, retrieving, and analyzing documents for their relevance, significance and meaning". Document analysis is often used in case studies and focuses on the information and data from formal documents and company records (Ramon Gil-Garcia 2012). Existing documents are a vital source of qualitative data and may be publicly available or private in nature (Woods and Graber 2017). Documents are one of the principal forms of data sources for the interpretation and analysis in case study research (Olson 2010). The documents collected for the present study were examined according to four criteria: authenticity, credibility, representativeness, and meaning (Fitzgerald 2012; Scott 2014)

Chester (2016, 577) has observed that authenticity refers to whether a document is genuine, complete, and reliable as well as being of unquestioned authorship. Authenticity also addresses whether their production is original, are not of questionable origin, and that they have not been subsequently altered. If a document has been found to be transformed, through textual editing, marginalia, or any other means, then the researcher is required to clearly identify those alterations (Kridel 2020). This criterion can largely be applied in assessing the value of historical material (Wellington 2015). Once it has been determined by the researcher that the document is "genuine and of unquestionable origin," then the material can be considered "valid" as an artifact. However, the document's content may still be questionable or subsequently found to be "incorrect" at a later stage (Kridel 2020).

Whilst any form of qualitative data may be original and genuine, that is, authentic, it is possible that the content may still be distorted in some manner. Thus, a second criterion in appraising materials is determining their credibility and identifying whether the document's information is both honest and accurate (Kridel 2020). Hence, credibility refers to the extent to which a document is sincere and not distorted and is free from error and evasion (Scott 2014). In assessing this criterion, it is necessary for the researcher to determine whether the document can be regarded as a credible, worthwhile piece of evidence and, also in some instances, whether it is accurate (Wellington 2015).

A third criterion, representativeness, refers to the "general problem of assessing the typicality or otherwise of the evidence" collected for the study (Scott 1990, 7). A document's representativeness may become distorted over time. This is because with the passing of time the survival rate of certain materials becomes greater as the items may have been viewed as less valuable. Accordingly, the document(s) may have been stored away, rarely viewed following their point of origination, and hence, preserved. Furthermore, some important documents do not survive because their great significance caused them to become well used and worn. Consequently, they may be discarded while on the other hand less important documents survive because they attract so little use (Kridel 2020).

A final criterion—meaning—refers to the degree to which the evidence is clear and comprehensible to the researcher(s) (Kridel 2020; Scott 1990). This criterion concerns the assessment of the actual documents gathered for the study by the researcher(s) (Wellington 2015). The four criteria – authenticity, credibility, representativeness and meaning – should not be regarded as separate and discrete stages when assessing documents. Rather, they are interdependent, and thus, a researcher cannot adequately consider one without simultaneously considering the others (Scott 2004). Hence, in this context, the assessment of documents is an ongoing, never-ending process. Scott (2004, 284) notes that "the interpretive meaning that the researcher aims to produce is a tentative and provisional judgment that must be constantly revised as new discoveries and new problems force a re-appraisal of the evidence". Most importantly, Scott (2004, 284) states that "an understanding of this is essential if a researcher is to make sensible use of documents".

An exhaustive source of the leading air transport and airport-related journals and magazines was also conducted. The study also included a search of the SCOPUS and Google Scholar databases.

The key words used in the database searches included "Fraport AG environmental management policy", "Fraport AG waste management policy", "Frankfurt Airport's waste management regulatory framework", "Frankfurt Airport's total annual hazardous wastes", "Frankfurt Airport's total annual non-hazardous wastes", "Frankfurt Airport's total annual disposed wastes", and "Frankfurt Airport's total annual reclaimed wastes".

The study's document analysis was conducted in six distinct phases. The first phase involved planning the types and required documentation and ascertaining their availability for the study. In the second phase, the data collection involved sourcing the documents from Fraport AG and developing and implementing a scheme for managing the gathered documents. The collected documents were examined to assess their authenticity, credibility and to identify any potential bias in the third phase of the document analysis process. In the fourth phase, the content of the collected documents was carefully examined, and the key themes and issues were identified and recorded in the case study. The fifth phase involved the deliberation and refinement to identify any difficulties associated with the documents, reviewing sources, as well as exploring the documents content. In the sixth, and final phase, the analysis of the data was completed (O'Leary 2004).

In this study, all the collected documents were downloaded and stored in a case study database (Yin 2018). The documents were all in English. Each document was carefully read, and key themes were coded and recorded (Baxter 2020).

4. RESULTS

4.1. A Brief Overview of Frankfurt Airport

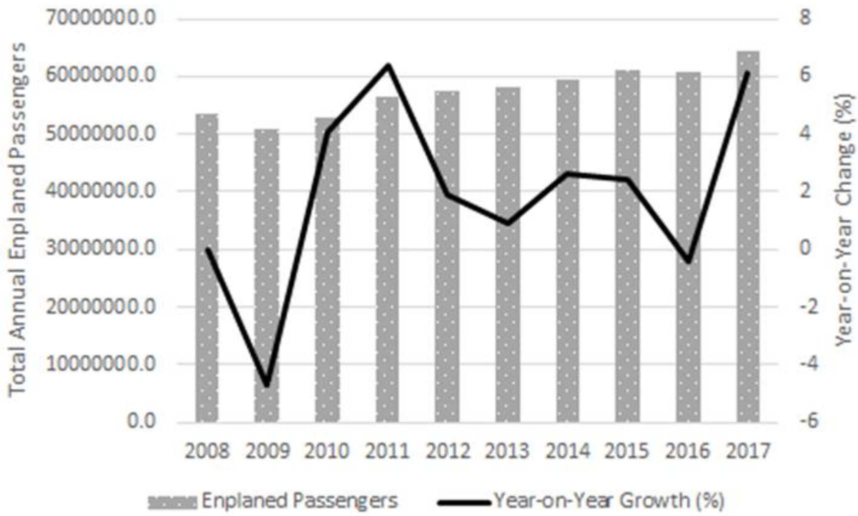
Frankfurt Airport is the busiest airport in Germany and ranks among the world's largest airports (Miyoshi and Prieto Torrell 2019; Zintel 2007). The airport is in Hesse at a location that was selected by the German government in 1936 (Niemeier 2014). Frankfurt is a major European air cargo facility and is served by more than 20 cargo airlines, as well as being a major hub of Lufthansa Cargo. The airport frequently ranks amongst the major airports for international destinations served, with more than 100 airlines operating scheduled, charter and cargo services. Europe, the Middle East, Asia, Africa, South America, and North America are served directly by the airlines operating from Frankfurt Airport (Centre for Aviation 2020). Frankfurt is the principal hub airport of German national carrier Lufthansa (Centre for Aviation 2020; Zintel 2007).

Frankfurt Airport has two operating passenger terminals. Terminal 1 is split into concourses A, B, C and Z and can handle around 50 million passengers per year. Terminal 2, which has a capacity of 15 million passengers a year, was opened in 1994, and this terminal includes concourses D and E (Frankfurt International Airport 2018). Frankfurt Airport has four runways: 07C/25C, 07L/25R, 07R/25L, and 18/36. The longest runway at Frankfurt Airport is Runway 07C/25C, which is 4,000 metres in length (Airport Guide 2020). Frankfurt Airport has the terminal and runway infrastructure to handle the largest aircraft types in operation, that is, the Airbus A380 and the Boeing 747-8.

Frankfurt Airport is owned and operated by Fraport AG (Airport Technology 2020). Fraport was founded in 1924 under the name Südwestdeutsche Luftverkehrs AG. The company originally operated Frankfurt Airport at the Rebstock site. Following the 1936 opening of Flug- and Luftschiffhafen Rhein-Main which is adjacent to the Frankfurter Kreuz autobahn intersection, the core of what is today's Frankfurt Airport (IATA airport code: FRA) began operations. Fraport AG is the owner of the airport site and provides the facilities to airlines and other key actors, including DFS German Air Navigation Services, as well as a large number of agencies and airport concessionaires (a total of more than 500 businesses and institutions) (Fraport AG 2019b).

At the time of the present study the major shareholders of Fraport AG were the State of Hesse (31.31%), Stadtwerke Frankfurt am Main Holding GmbH (20.32%), Deutsche Lufthansa AG (8.44%), Lazard Asset Management (5.02%) and BlackRock Inc. (3.05%). The remaining 31.86% of the company's shares are held in private portfolios and by other institution (Fraport AG 2020c).

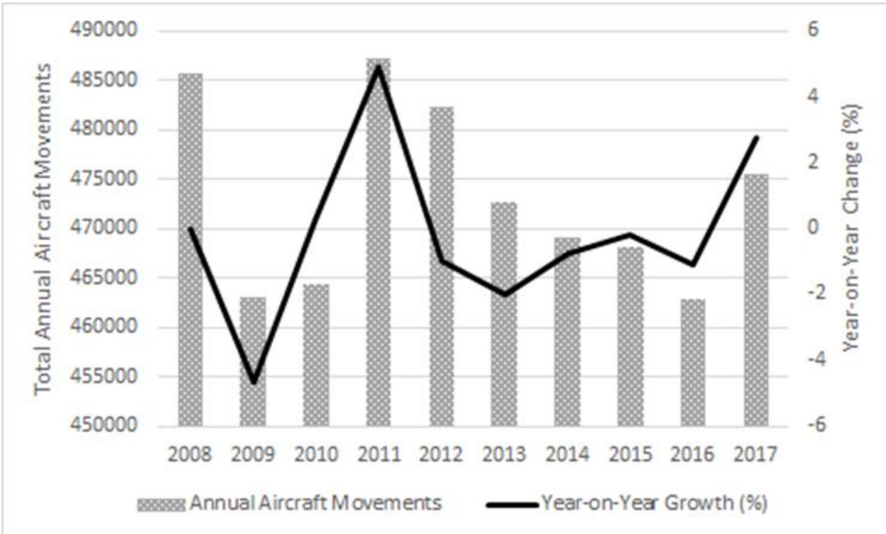
Figure 2 presents Frankfurt Airport total annual enplaned (domestic and international) passengers and the year-on-year change (%) for the period 2008 to 2017. One passenger enplanement measures the embarkation of a revenue passenger, whether originating, stop-over, connecting or returning (Holloway 2016). As can be observed in Figure 2, the growth in Frankfurt Airport's annual enplaned passengers exhibited an upward trend, increasing from 53.4 million in 2008 to 64.5 million in 2017. Figure 2 also shows that there was a decrease in the number of passengers in 2009, when the number of passengers handled at the airport declined by 4.74% on the 2008 levels. The global airline industry was adversely impacted by the global financial crisis in 2008 and 2009, which resulted in a downturn in passenger demand (Morrell 2013; Samunderu 2020; Serebrisky 2012). There was also a small decrease in enplaned passengers recorded in 2016 (-0.4%) (Figure 2).



Source: Data derived from Fraport A.G. (2010, 2012, 2015, 2018).

Figure 2. Frankfurt Airport's total annual enplaned passengers and year-on-year change (%): 2008-2017.

Frankfurt Airport's total annual aircraft movements and the year-on-year change (%) are depicted in Figure 3. The aircraft movements at Frankfurt Airport include domestic and international commercial passenger flights, domestic and international commercial air cargo flights, domestic and international general aviation flights as well as State Aviation Flights, which may be operated domestically or internationally (Fraport AG 2019a). As can be observed in Figure 3, the annual number of aircraft movements at Frankfurt oscillated quite widely during the period 2008 to 2017. The highest number of annual aircraft movements at Frankfurt Airport was recorded in 2011, when the airport handled a total of 487,162 aircraft movements. The lowest annual number of aircraft movements occurred in 2016, when the airport handled a total of 462,885 aircraft movements. Figure 3 also shows that there were annual decreases in the number of aircraft movements in 2009 (-4.67%), 2012 (-1%), 2013 (-1.98%), 2014 (-0.77%), 2015 (-0.18%), and 2016 (-1.12%), respectively. The oscillations in the number of aircraft movements reflect airline operational patterns and passenger and air cargo demand profiles. Other factors affecting aircraft movements are airport slot constraints, market demographics, airport characteristics, airline characteristics, and route characteristics. Moreover, hub airports, like Frankfurt Airport, are associated with larger aircraft sizes and higher flight frequencies. Airport delays can also result in airlines reducing flight frequencies whilst also operating smaller aircraft, though during times when airport cancellations increase, flight frequency increases with the use of larger aircraft types (Pai 2010). Airlines are also able to accommodate increased passenger demand by either increasing the frequency of the aircraft size, which may involve different numbers of aircraft movements (Kölker, Bießlich and Lütjens 2016).



Source: Data derived from Fraport A.G. (2010, 2012, 2015, 2018).

Figure 3. Frankfurt Airport's total annual aircraft movements and year-on-year change (%): 2008-2017.

4.2. Fraport AG Environmental Management

Since 1999, Fraport AG as the manager and operator of Frankfurt Airport, has been regularly validated by government accredited and inspected environmental management auditors. The basis for such audits is the European regulation "Eco-Management and Audit Scheme" (EMAS) (Fraport AG 2018). EMAS is a voluntary instrument of the European Union, which enables firms of any size and industry to examine and continuously enhance their environmental performance (International Airport Review 2014). Since 2002, Frankfurt Airport's environmental audits have been carried out in accordance with the international standard ISO 14001 (Fraport AG 2018). ISO 14001 is a global meta-standard for implementing Environmental Management Systems (EMS) (Heras-Saizarbitoria, Arana Landín and Francisco Molina-Azorín 2011). Environmental Management Systems (or EMSs) have become an important tool for those firms seeking to manage their environmental issues such as pollution prevention, legal compliance, and minimizing the impacts their activities cause to the environment (Campos 2012). Fraport AG's audits, which are in conformity with EMAS and ISO 14001, also include the following Fraport AG subsidiaries: Fraport Cargo Services GmbH (FCS) since 2008, N*ICE Aircraft Services & Support GmbH (N*ICE) since 2009, and Energy Air GmbH since 2014. Energy Air GmbH is also validated in accordance with the international standard ISO 50001. There were several new additions to the EMAS network in 2017 which included the subsidiary firms Fraport Ground Services GmbH

(FraGround) and GCS Gesellschaft für Cleaning Service GmbH & Co (Airport Frankfurt/Main KG [GCS]) (Fraport AG 2018).

4.3. Frankfurt Airport Waste Management Regulatory Framework

Transforming waste into a resource is one key principle of the circular economy. The objectives and goals prescribed in European legislation have been key drivers to improve waste management, stimulate innovation in the recycling of wastes, placing limitations on the use of landfilling, and creating incentives to change consumer behaviour. The European waste policy encourages the re-manufacture, reuse, and recycling of wastes. Importantly, an industry's waste can become another's raw material, then in such a case it is possible to move to a more circular economy where waste is eliminated, and resources are used in an efficient and sustainable way. The European Union's approach to waste management is based on the "waste hierarchy". As noted earlier, this hierarchy sets the following priority order when shaping waste policy and managing waste at the operational level: prevention, (preparing for) reuse, recycling, recovery and, as the least preferred option, disposal (which includes landfilling and incineration without energy recovery) (European Commission 2020). The European Union has set the following waste management priority objectives which are in accordance with the "7th Environment Action Programme":

- To reduce the amount of waste generated.
- To maximise recycling and re-use.
- To limit incineration to non-recyclable materials.
- To phase out landfilling to non-recyclable and non-recoverable waste.
- To ensure full implementation of the waste policy targets in all Member States (European Commission 2020).

In Europe, the disposal of waste is governed through European regulations and directives. The European regulations automatically apply to each of the member states, whilst the directives must be separately transposed into national law by each member state. The basis of this legal framework is the Waste Framework Directive (2008/98/EC). This framework defines the key waste-related terms, lays down a five-step waste hierarchy, and contains key provisions for German waste disposal law (Umwelt Bundesamt 2020).

Since the early 1990s, there have been significant changes in waste management in Germany. The German Waste Management Act (Kreislaufwirtschaftsgesetz – KrWG) came into effect in June 2012 (Fraport AG 2020a). One of the core provisions of Germany's Waste Management Act (KrWG) is the five-step (previously three step) hierarchy which is pursuant to Article 6, according to which the following ranking of waste management measures applies: waste prevention, preparation of waste for recycling, recycling, other types of recovery, especially the use for energy recovery, and finally, waste disposal (Umwelt Bundesamt 2020)

This legislation led to an end to the "throwaway society" and was a major step towards the implementation of the circular economy (Fraport AG 2020a).

Working in close collaboration with airlines, suppliers, and other firms, Fraport AG is committed to avoiding waste in the first place. If any waste is produced, the company will do its utmost to recycle the materials it contains or alternatively turn such wastes into energy or into heating for its facilities (Fraport AG 2020a).

4.4. Frankfurt Airport Waste Handling Methods

The key strategy underpinning Fraport AG's waste management at Frankfurt Airport is to recycle or reuse unavoidable wastes wherever possible. At Frankfurt Airport, non-hazardous wastes, for example, cardboard, glass, packaging waste (DSD green dot waste), paper, plastics, and mixed industrial wastes are carefully separated. The waste that is collected is fed either into advanced sorting systems, in which contaminated wastes are separated out and reusable materials are recycled or transported to regional waste-to-energy plants. Both electricity and district heating are extracted from the energy that is produced during the incineration process (Fraport AG 2020a).

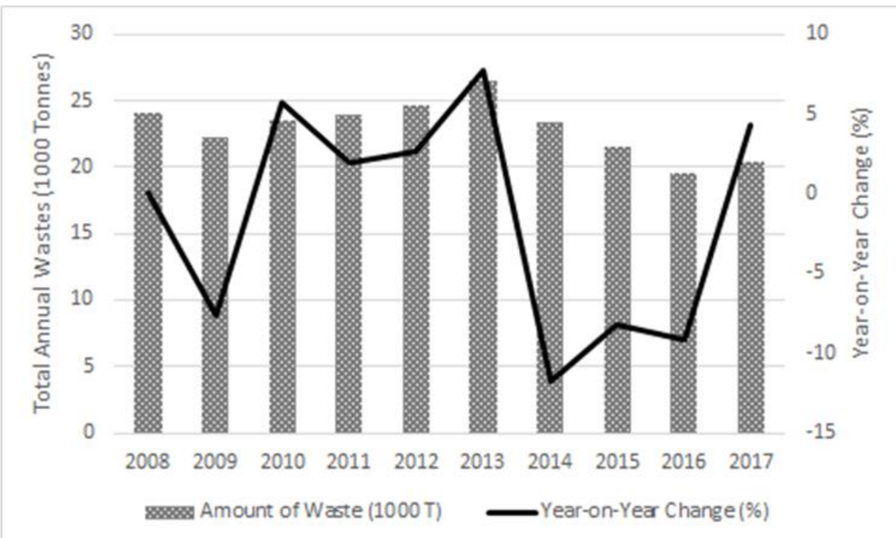
The hazardous wastes that are produced at Frankfurt Airport are collected separately and such wastes are channelled away for recycling as far as possible. In cases where recycling is not possible, this waste is disposed of in approved incineration or in physical and chemical treatment plants (Fraport AG 2020b).

4.5. Annual Volumes of Waste Generated at Frankfurt Airport

Figure 4 presents Frankfurt Airport's total annual wastes and the year-on-year change (%) from 2008-2017. As can be observed in Figure 4, Frankfurt Airport's total annual wastes decreased from 24,110 tonnes in 2008 to 20,360 tonnes in 2017. The highest quantity of annual wastes was in 2013, when the airport handled 26,540 tonnes of wastes. The lowest annual wastes amount was recorded in 2016, when the airport's handled 19,520 tonnes of waste. Figure 4 also reveals that towards the latter years of the study, there were decreases recorded in the annual wastes handled at the airport. These decreases occurred in 2014 (-11.79%), 2015 (-8.2%), and 2016 (-9.16%) (Figure 4), respectively. The overall decreases in the total quantities of wastes are a favourable outcome given the increase in the number of passengers handled by the airport during the study period. This suggests that the airport has been successfully able to accommodate passenger traffic growth whilst at the same time sustainably manage the wastes generated from the activities undertaken at the airport.

4.6. Hazardous Wastes at Frankfurt Airport

Hazardous waste management involves the reduction in the quantity of hazardous materials produced, the treatment of hazardous wastes to reduce their toxicity, as well as the application of sound engineering controls to reduce or eliminate exposures to such wastes (Vallero 2011). As previously noted, the actors operating at an airport produce hazardous wastes as a by-product of their activities, and thus, hazardous waste management principles need to be carefully applied to mitigate the harmful effects of such wastes. The quantity of hazardous wastes handled at Frankfurt Airport and the year-on-year changes from 2008-2017 are depicted in Figure 5. As can be observed in Figure 5, the annual hazardous wastes at Frankfurt Airport have fluctuated throughout the study period reflecting the key stakeholders operating at Frankfurt Airport's hazardous goods requirements. The lowest annual quantity of hazardous wastes was in 2009, when the airport handled 1,204 tonnes of hazardous wastes. The highest annual quantity of hazardous wastes occurred in 2013, when the airport handled 2,730 tonnes of hazardous wastes. Figure 6 shows that there was a pronounced spike in hazardous wastes in 2013, when they increased by 100.73% on the previous year levels. Other significant increases were recorded in 2010 (+33%) and in 2017 (+45.03%), respectively (Figure 5). Figure 5 also shows that significant reductions in the quantity of hazardous wastes were recorded in 2009 (-36.73%), 2011 (-25.28%), and 2014 (-41.79%), respectively. Despite the fluctuations in the annual amounts of hazardous wastes produced by the key actors at Frankfurt Airport, such wastes are handled in an environmentally sustainable manner as they are either recycled or disposed of in approved incineration or in physical and chemical treatment plants, which have the capability to process the hazardous wastes generated at Frankfurt Airport.

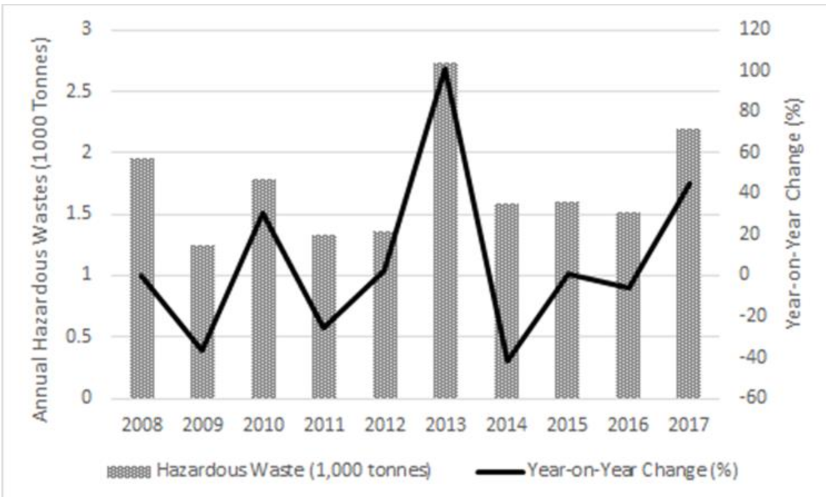


Note: Includes wastes produced by third parties. Principally residual waste out of aircraft but excluding catering waste and without soil and building rubble. Wastes are for the Fraport parent company.
Source: Data derived from Fraport A.G. (2009, 2010, 2012, 2015, 2018).

Figure 4. Frankfurt Airport's total annual wastes and year-on-year change (%): 2008-2017.

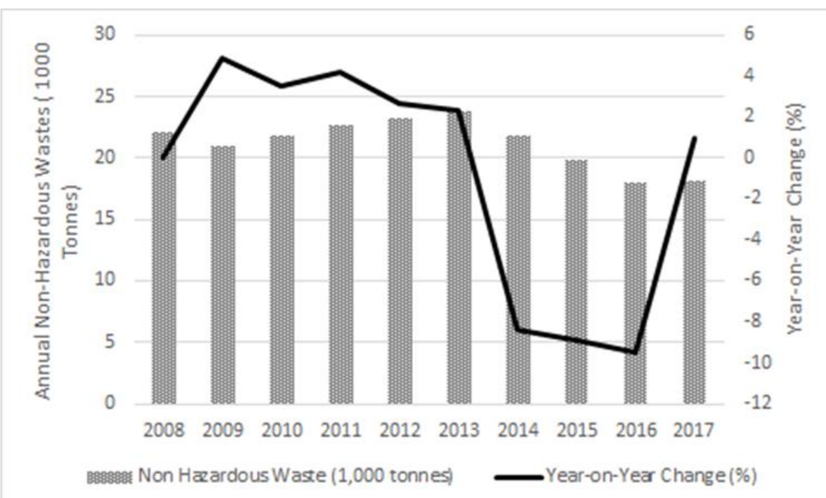
4.7. Non-Hazardous Wastes at Frankfurt Airport

Frankfurt Airport's total annual non-hazardous wastes and the year-on-year changes (%) from 2008-2017 are depicted in Figure 6. As can be observed in Figure 6, there were two discernible trends in the annual quantities of non-hazardous wastes handled at Frankfurt Airport during the study period. During the first phase from 2008 to 2013, there was a general upward trend when the annual quantities of non-hazardous wastes increased on a year-on-year basis, with the most significant annual increase occurring in 2009. In 2009, the amount of non-hazardous waste increased by 4.88% on the 2008 levels. In the second phase, the annual quantities of non-hazardous wastes decreased on a year-on-year basis in 2014 (-8.35%), 2015 (-8.89%), and again in 2016 (-9.45%) before increasing slightly in 2017 by 0.94% (Figure 6). The general downward trend in the quantity of non-hazardous wastes from 2013 onwards is a very favourable trend given that Frankfurt Airport has increased its annual volumes of passenger and air cargo traffic during this period. This suggest that it is possible to expand both passenger and air cargo traffic whilst at the same time minimizing non-hazardous wastes through careful sustainable waste management policies and practices.



Source: Data derived from Fraport A.G. (2009, 2010, 2012, 2015, 2018).

Figure 5. Frankfurt Airport's total annual hazardous wastes and year-on-year change (%): 2008-2017.

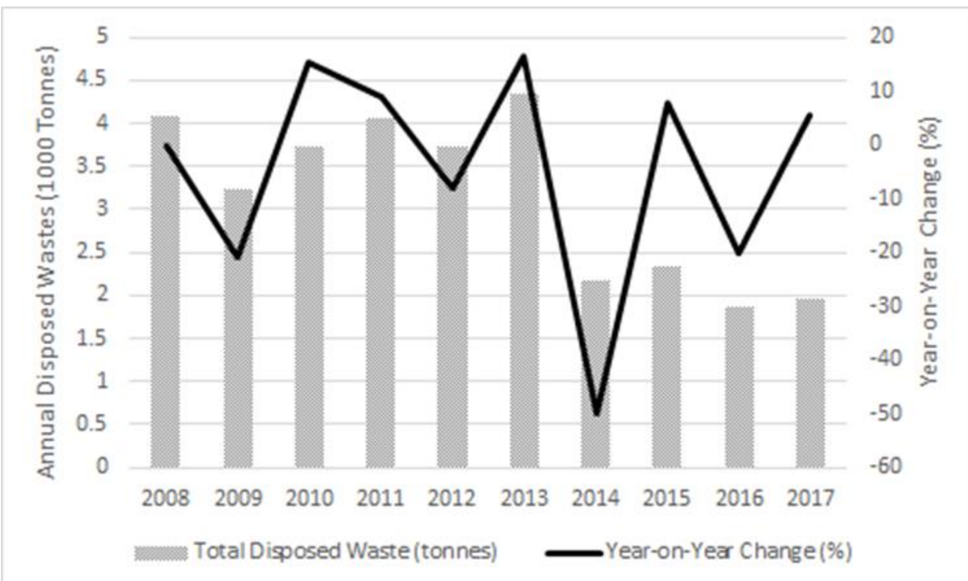


Source: Data derived from Fraport A.G. (2009, 2010, 2012, 2015, 2018).

Figure 6. Frankfurt Airport's total annual non-hazardous wastes and year-on-year change (%): 2008-2017.

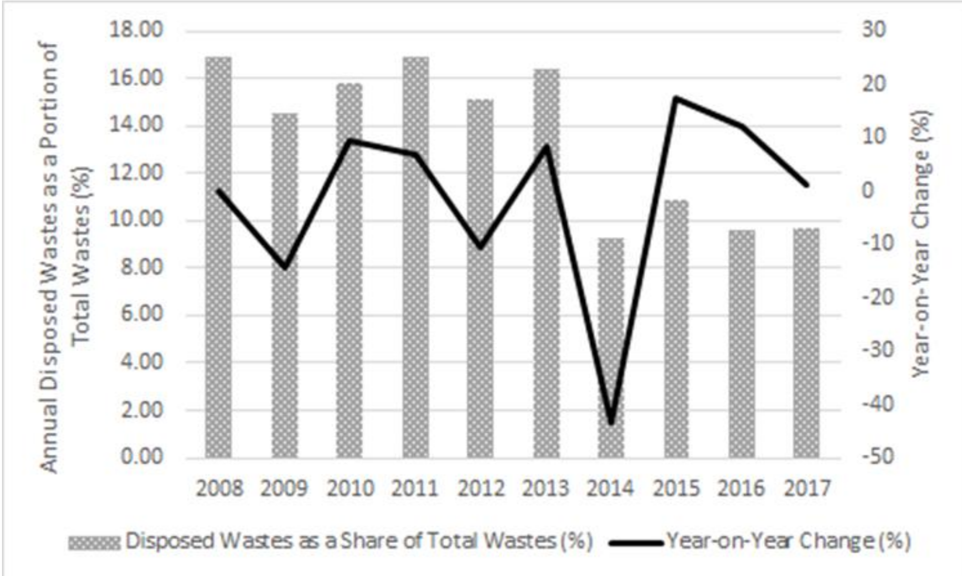
4.8. Disposed Wastes at Frankfurt Airport

Prior to examining Fraport AG's annual disposed wastes it is important to note that such wastes are transported to regional waste-to-energy plants. As noted earlier, hazardous wastes that cannot be recycled are disposed at an approved incineration facility or in physical and chemical treatment plants (Fraport AG 2020b). Figure 7 shows Frankfurt Airport's annual disposed wastes and the year-on-year changes (%) from 2008-2017. Figure 7 shows that there have been two discrete phases in the annual disposed wastes handled at Frankfurt Airport. From 2008 to 2013, there was a general upward trend in the quantity of disposed wastes, which increased from 4,080 tonnes in 2008 to a high of 4,350 tonnes in 2013. Following a decrease of 20.83% in 2009, disposed wastes grew by 15.47% in 2010, 8.84% in 2011, and by 16.62% in 2013, respectively (Figure 7). There were two substantial decreases recorded in the second phase when the airport's annual non-hazardous wastes decreased by 50.11% in 2014 and by 20.08% in 2016, respectively. The lowest quantities of disposed wastes were recorded in 2016 (1,870 tonnes) and 2017 (1,970 tonnes) (Figure 7), respectively. The overall downward trend in disposed wastes in the second phase is most favourable given the increase in the number of passengers handled at the airport. This downward trend also shows that greater volumes of wastes are being recycled and this trend is discussed in the next section.



Source: Data derived from Fraport A.G. (2009, 2010, 2012, 2015, 2018).

Figure 7. Frankfurt Airport's total annual disposed wastes and year-on-year change (%): 2008-2017.



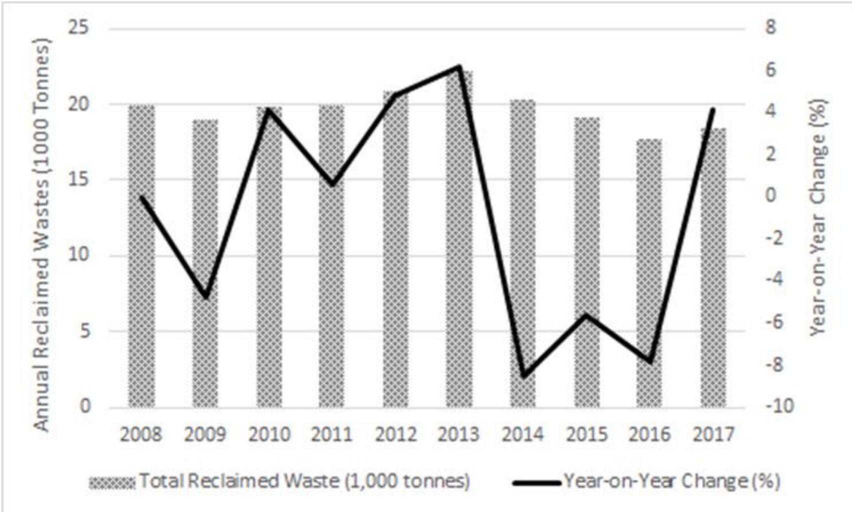
Source: Data derived from Fraport A.G. (2009, 2010, 2012, 2015, 2018).

Figure 8. Frankfurt Airport's total annual disposed wastes as a portion of total wastes and the year-on-year change (%): 2008-2017.

The total annual wastes disposed as a portion of the total wastes produced at Frankfurt Airport and the year-on-year difference (%) for the period 2008 to 2017 are presented in Figure 8. As can be observed in Figure 8, the disposed wastes as a portion of total wastes declined from 16.92% in 2008 to 9.68% in 2017. In 2011, the disposed wastes as a portion of total wastes were also 16.92% (Figure 8). The disposed wastes lowest annual portion of total wastes was recorded in 2014, when the annual disposed wastes accounted for 9.27% of the total wastes generated at Frankfurt Airport. The largest single increase in the portion of disposed wastes of the airport's total wastes occurred in 2015, when this waste portion increased by 17.47% on the 2013 level. Figure 8 also shows that there was a significant decrease in the portion of disposed wastes (-43.44%), this was the largest single annual decrease recorded in the study period.

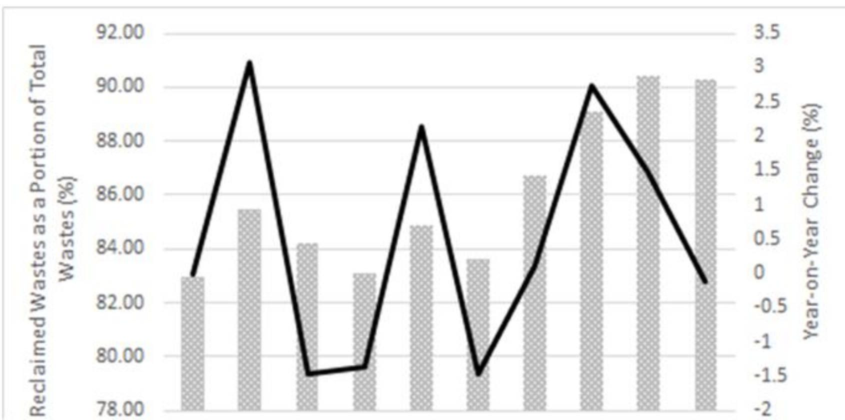
4.9. Reclaimed Wastes at Frankfurt Airport

Frankfurt Airport's primary sustainable waste handling method is reclaiming wastes for subsequent recycling. The airport's total annual reclaimed wastes and the year-on-year changes (%) from 2008-2017 are presented in Figure 9. As can be seen in Figure 9, Frankfurt Airport's annual reclaimed wastes have remained quite constant over the study period averaging around 19,730 tonnes per annum. From 2010 to 2013, the annual reclaimed wastes increased on a year-on-year basis, with the most significant increase in this period occurring in 2013 (+6.17%). However, during 2014 and 2015, there was a small decline in the airport's annual reclaimed wastes which was followed by a strong increase of 4.19% in 2017 (Figure 9).



Source: Data derived from Fraport A.G. (2009, 2010, 2012, 2015, 2018).

Figure 9. Frankfurt Airport's total annual reclaimed wastes and year-on-year change (%): 2008-2017.



Source: Data derived from Fraport A.G. (2009, 2010, 2012, 2015, 2018).

Figure 10. Frankfurt Airport's total annual reclaimed wastes as a portion of total wastes and the year-on-year change (%): 2008-2017.

Frankfurt Airport's total annual reclaimed wastes as a portion of total wastes and the year-on-year change (%) from 2008-2017 are depicted in Figure 10. Figure 10 shows that reclaimed wastes as a portion of Frankfurt Airport total annual wastes increased from 82.95% in 2008 to 90.32% in 2017. In 2016, 90.42% of the annual wastes generated at the airport were reclaimed. This was the highest annual level of reclaimed wastes as a portion of total wastes during the study period. The lowest level of reclaimed wastes as a portion of total wastes occurred in 2011, when such wastes accounted for 83.08% of the airport's annual wastes. Figure 10 also shows that during the later years of the study period (2014-2017) there was a general upward trend in the quantities of wastes that were reclaimed for subsequent recycling.

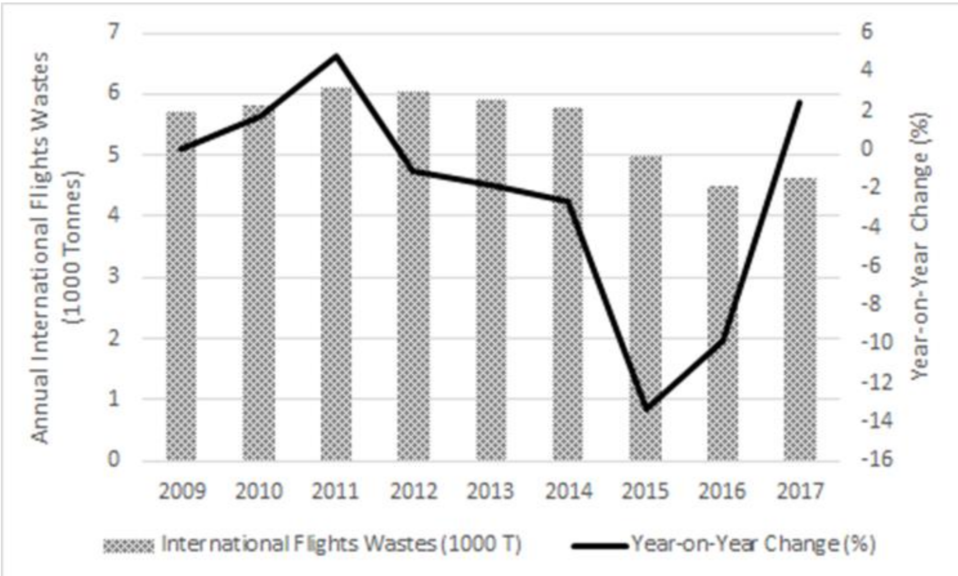
Overall, the amount of reclaimed wastes accounts for the largest share of disposed wastes at the airport, and the reclaiming of wastes provides significant environmental benefits. These benefits include a reduction in the quantity of wastes sent for incineration, the conservation of natural resources, energy savings, a reduction in pollution by reducing the requirement to collect new raw materials (Environmental Protection Agency 2020).

4.10. Wastes from International Flights at Frankfurt Airport

Frankfurt Airport is a major global air transport hub with more than 100 airlines providing a mixture of short-haul, regional, and long-haul intercontinental services to and from the airport. A by-product of the provision of passenger and air cargo services is the generation of wastes, which need to be handled in accordance with Germany's waste legislation and Fraport AG's waste management policy. Figure 11 shows the quantity of wastes originating from international flights that were handled at Frankfurt Airport from 2009-2017. Figure 11 shows that there have been two distinct phases in these wastes. In Phase 1, there was an upward trend in the quantity of wastes from international flights increasing from 5,730 tonnes in 2009 to 6,110 tonnes in 2011 (the highest level during the study period). In the second phase from 2012 to 2017, the annual quantity of wastes from international flights displayed an overall downward trend with annual decreases recorded in the period 2012 to 2016 after which there was a small increase of 2.43% recorded in 2017 (Figure 11). Throughout the study period, there has principally been a downward trend in the amount of wastes from international flights at Frankfurt Airport. This is demonstrated by the year-on-year percentage change line graph, which is more negative than positive, that is, more values are below the line than above. This suggests that the international airlines, both passenger and all-cargo, are sustainably managing their wastes and, as a result, there have been lower volumes of wastes to be handled at Frankfurt Airport. This is a very favourable trend given the increases in both passenger and air cargo traffic at Frankfurt Airport recorded during the study period.

4.11. Total Waste Measures for Frankfurt Airport

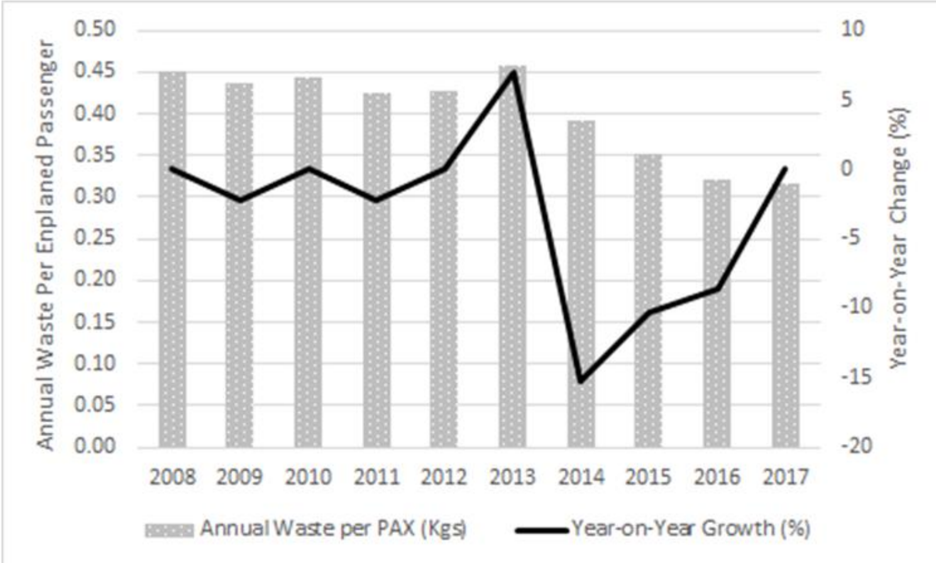
One of the primary indicators of waste management efficiency at airports is the waste generated per passenger (Graham 2005; Janić 2011). This measure is preferred to be as low as possible and to decrease with the airport's output over a given period, which is typically a year (Janić 2011). Figure 12 presents the total wastes relative to Frankfurt Airport's annual passenger throughput and the year-on-year change (%) for the period 2008 to 2017. Figure 12 shows that Frankfurt Airport has been able to successfully lower the amount of waste per passenger despite the increase in the volume of passengers handled annually at the airport. The annual waste per passenger has decreased from 0.45kgs per enplaned passenger in 2008 to 0.32kgs per enplaned passenger in 2017. During the study period, the highest annual waste per enplaned was recorded in 2013, when the annual waste per enplaned passenger was 0.46 kgs. The annual decrease in wastes per enplaned passenger are demonstrated by the year-on-year percentage change line graph, which is more negative than positive, that is, more values are below the line than above. During the study period, there was just one year when the annual amount of waste per enplaned passenger increased. This occurred in 2013, when the annual waste per enplaned passenger increased by 6.97% on the previous year's level. Figure 12 also shows that the annual amount of waste per enplaned passenger remained constant in 2010, 2012, and in 2017, that is, the amount of waste per enplaned remained the same as the previous years (2009, 2011, and 2016). This was also a favourable trend given the increase in passengers handled at the airport during 2010, 2012, and 2017.



Note: 2008 data not available.
Source: Data derived from Fraport A.G. (2009, 2010, 2012, 2015, 2018).

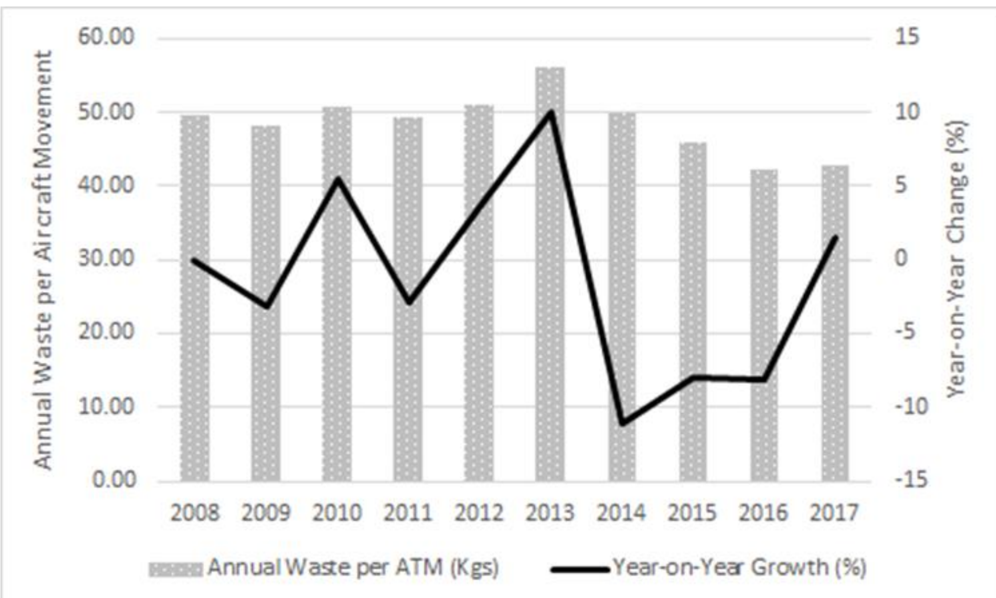
Figure 11. Annual wastes from international flights at Frankfurt Airport and year-on-year change (%): 2009-2017.

Figure 13 shows the trends in the total waste per aircraft movement (ATM) at Frankfurt Airport from 2008 to 2017. As can be observed in Figure 13, the quantity of total waste per aircraft movement (total per ATM) has decreased over time. Figure 13 shows that the amount of waste per aircraft movement in 2008 was 41.17kgs, whilst in 2017 this had declined to 38.67kgs per aircraft movement. The highest annual amount of waste per aircraft movement occurred in 2014 (47.55 kgs per aircraft movement), whilst the lowest annual amount of waste per aircraft movement was recorded in 2016, when there was 38.13kgs of waste per aircraft movement. As noted earlier, during the study period, there was a general decrease in the number of aircraft movements at Frankfurt Airport, this was especially so for the latter years of the study, that is, 2012 to 2017. Throughout the study period, there was also a general decrease in the annual amount of wastes produced at Frankfurt Airport. Thus, despite the reduced numbers of aircraft movements, Frankfurt Airport has also been able to reduce the annual wastes per aircraft movement, which is an environmentally efficient outcome.



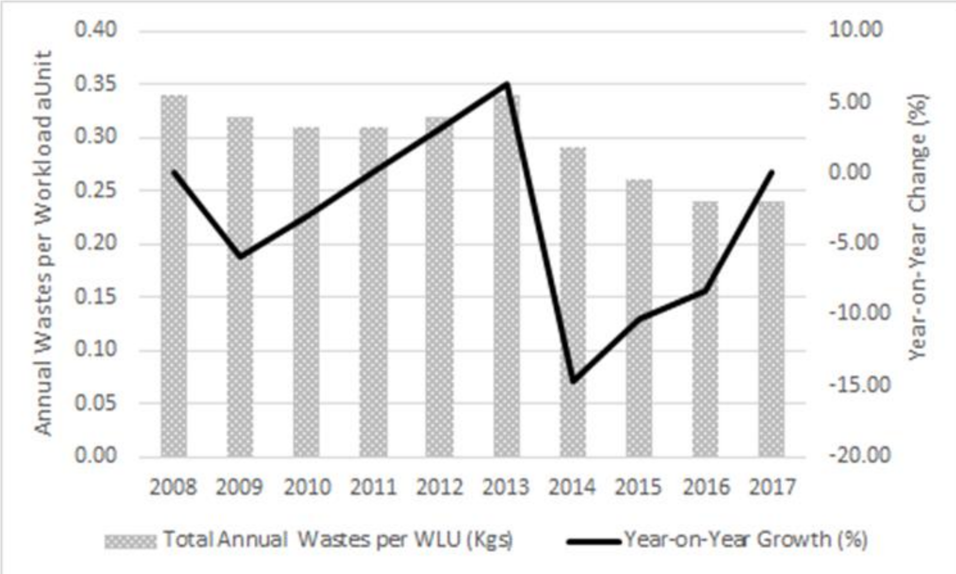
Source: Data derived from Fraport A.G. (2009, 2010, 2012, 2015, 2018).

Figure 12. Total waste per enplaned passenger and year on year percentage difference at Frankfurt Airport: 2008-2017.



Source: Data derived from Fraport A.G. (2009, 2010, 2012, 2015, 2018).

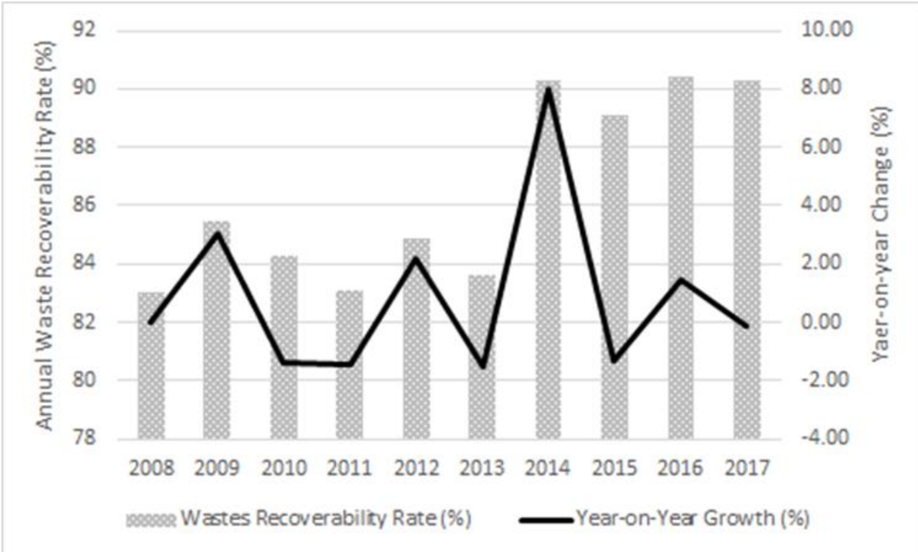
Figure 13. Total wastes per aircraft movement and year on year percentage difference at Frankfurt Airport: 2008-2017.



Source: Data derived from Fraport A.G. (2009, 2010, 2012, 2015, 2018).

Figure 14. Total waste per workload unit (WLU) and year on year percentage difference at Frankfurt Airport: 2008-2017.

Figure 14 shows the total waste per workload unit (WLU) or traffic unit. A workload unit (WLU) is equivalent to one terminal passenger or 100kgs of air freight (Doganis 2005). The passenger traffic workload unit (WLU) is based on a passenger weight of 80kgs and their baggage weight of 20kgs (Janić 2017). Figure 14 shows that the annual wastes per workload unit (WLU) at Frankfurt Airport have decreased from 2008 to 2017. The highest annual wastes per workload unit (WLU) were recorded in 2008 and 2013 (0.34kgs per WLU), whilst the lowest annual quantity of wastes per workload unit (WLU), was recorded in 2016 and 2017, when the annual quantity of wastes per workload unit was 0.24kgs per WLU. The annual decrease in wastes per workload unit (WLU) are demonstrated by the year-on-year percentage change line graph, which is more negative than positive, that is, more values are below the line than above. During the study period, there was just two years when the annual amount of waste per workload (WLU) increased. These increases were recorded in 2012 (+3.22%) and 2013 (+6.25%), respectively. The overall decrease in the waste per workload unit (WLU) is a very favourable trend for Frankfurt Airport, as it demonstrates that the despite the general increase in the volume of the traffic handled at the airport, the airport has successfully been able to handle this traffic without a concomitant increase in the waste per workload or traffic unit.

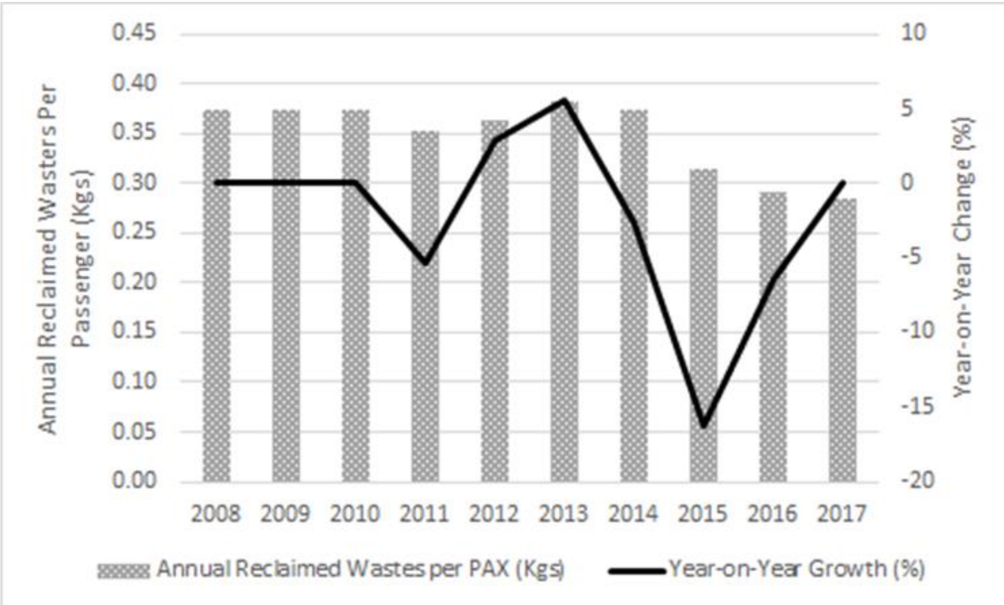


Source: Data derived from Fraport A.G. (2009, 2010, 2012, 2015, 2018).

Figure 15. Total annual waste recoverability rate (%) and year on year percentage difference at Frankfurt Airport: 2008-2017.

The proportion of waste reclaimed or recycled is another important airport related environmental metric (Graham 2005; Hazel et al., 2011; International Civil Aviation Organization 2020). Frankfurt Airport's annual waste recoverability rate (%) and the year-on-year difference (%) for the period 2008 to 2017 are depicted in Figure 15. Figure 15 shows that there has been a general upward trend in the waste recoverability rate at Frankfurt Airport throughout the study period, increasing from 83% in 2008 to 90.3% in 2017. The highest annual waste recovery rate was recorded in 2016, when the airport was able to recover 90.4% of the wastes generated (Figure 15). The single highest annual increase in the wastes recoverability rate (%) occurred in 2014, when the annual waste recoverability rate (%) increased by 8.01% on the previous year's level. The largest single annual decrease in the airport's waste recoverability rate (%) was recorded in 2013, when the annual recoverability rate (%) decreased by -1.53% on the 2012 level. Figure 15 also reveals that Frankfurt Airport's waste measures and strategies have resulted in the very significant level of wastes recovered for re-use and recycling. This ensures that the potential adverse impact of wastes disposal and handling is very well mitigated by the airport.

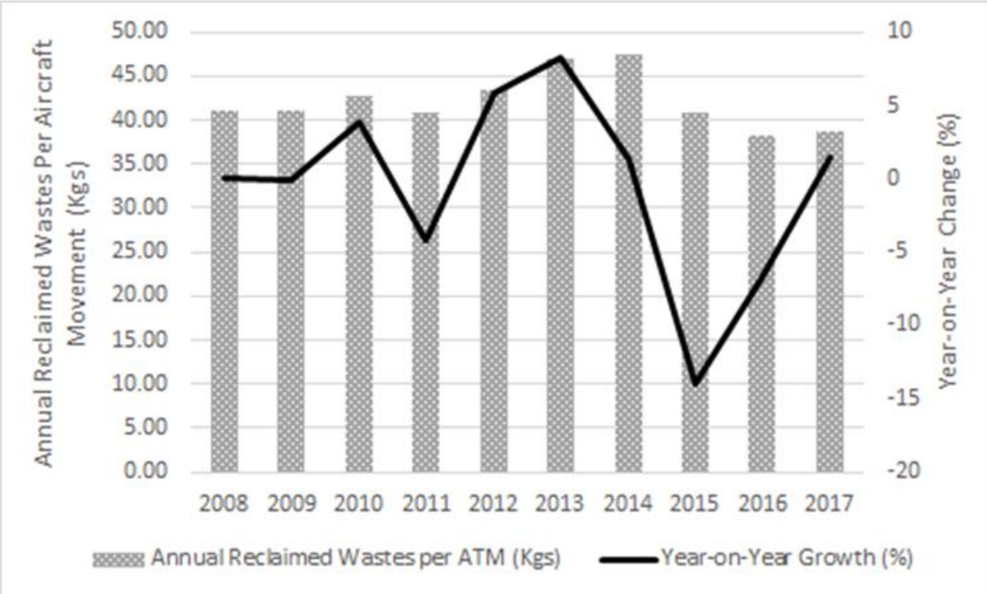
Two other important airport waste-related metrics are the reclaimed or recycled wastes per enplaned passenger and recycled wastes per aircraft movement (ATM) (Baxter et al., 2018). Figure 16 shows that Frankfurt Airport's annual reclaimed wastes per enplaned passenger remained relatively constant from 2008 to 2014 before decreasing slightly over the period 2015 to 2018. Figure 16 also shows that the highest annual reclaimed wastes per passenger was recorded in 2013 (0.38 kgs per enplaned passenger), whilst the lowest annual reclaimed wastes per passenger were recorded in 2016 (0.29kgs per enplaned passenger) and 2017 (0.29kgs per enplaned passenger), respectively. The decrease in the level of reclaimed wastes per enplaned passenger is due to the overall decrease in reclaimed wastes and the increased number of passengers handled at Frankfurt Airport, Hence, the greater level of passengers handled (output) combined with the lower level of reclaimed wastes results in a lower level of reclaimed wastes per passenger as the wastes are spread over a greater volume of passenger traffic. Once again, this highlights how Frankfurt Airport has been able to grow its passenger volumes whilst at the same time reducing wastes per passenger through lower wastes volumes and its environmental waste management measures.



Source: Data derived from Fraport A.G. (2009, 2010, 2012, 2015, 2018).

Figure 16. Total annual reclaimed wastes per enplaned passenger (PAX) and year on year percentage difference at Frankfurt Airport: 2008-2017.

Frankfurt Airport's annual reclaimed wastes per aircraft movement (ATM) and the year-on-year difference (%) for the period 2008 to 2017 are presented in Figure 17. As can be observed in Figure 17, there are two discernible trends in annual wastes per aircraft movement (ATM). The first trend covers the period 2008 to 2014, at which time there was a general upward increase in the annual amount of waste per aircraft movement. This trend reflects the general upward increase in aircraft movements during 2008 to 2014. The second trend covers the latter years of the study (2015 to 2017) and reveals that there was a decrease in the annual amount of wastes per aircraft movement (ATM). This decrease was due to the lower number aircraft movements using the airport as well as the annual volumes of reclaimed wastes, which when taken together, resulted in lower amounts of waste per aircraft movement (ATM). The largest single annual increase in the reclaimed wastes per aircraft movement (ATM) occurred in 2012, when this metric increased by 5.88% on the 2011 levels. The largest single annual decrease in the wastes per aircraft movement was recorded in 2015, when the annual wastes per aircraft movement (ATM) decreased by 13.96% on the previous year levels (Figure 17).



Source: Data derived from Fraport A.G. (2009, 2010, 2012, 2015, 2018).

Figure 17. Total annual reclaimed wastes per aircraft movement (ATM) and year on year percentage difference at Frankfurt Airport: 2008-2017.

CONCLUSION

One of the most critical environmental issues confronting airports all around the world is waste management. Each year, airports generate large volumes of hazardous and non-hazardous wastes all of which must be handled in an environmentally sustainable manger. Accordingly, airports are increasingly focusing on waste management as a core element of their environmental policies and strategies. This study has examined how Frankfurt Airport, a major global air transport hub, sustainably manages its general (non-hazardous) and hazardous wastes. Throughout the study period of 2008 to 2017, Frankfurt Airport's principal waste management strategy was to reclaim and recycle wastes wherever possible. Wastes that cannot be recycled are disposed through incineration plants that converts the wastes into energy that is used to generate electricity and heat. The study found that Frankfurt Airport was successfully able to increase its total wastes recoverability rate from 83% in 2008 to 90.3% in 2017. Importantly, no wastes are disposed to landfill by the airport, and thus, the reclamation of wastes and the use of waste-to-energy facilities for non-reclaimable wastes underpin the ability of Frankfurt Airport to mitigate the environmental impact of both the hazardous and non-hazardous wastes generated at the airport.

Throughout the study period, the annual number of passengers handled at Frankfurt increased quite significantly, however, despite this growth in passenger traffic, the airport was able to reduce the annual waste per enplaned passenger from 0.45 kgs per passenger in 2008 to 0.32 kgs per enplaned passenger in 2017. Frankfurt Airport was also able to reduce the waste per workload unit (WLU) from 0.34 kgs per workload unit (WLU) in 2008 to 0.24 kgs per workload unit (WLU) in 2017. The study also revelated that Frankfurt Airport has been able to decrease the waste per aircraft movement from 49.63 kgs per aircraft movement (ATM) in 2008 to 42.81 kgs per aircraft movement (ATM) in 2017. These are very favourable results and highlight the fact that the airport has been able to increase its passenger traffic and aircraft movements whilst at the same time reducing the wastes arising from the activities undertaken at the airport.

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Chapter 8

THE ROLE OF MICROORGANISMS IN BIOREMEDIATION

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ABSTRACT

Environmental pollution caused by toxic chemicals waste from biological, chemical and industrial processes has become an area of concern all over the world. Various chemical and biological processes have been developed and discovered to minimise the pollution caused due to the unwanted waste. Bioremediation is one of the most applicable and eco-friendly process of recycling non-usable wastes into reusable form. It uses the microorganisms to solve the problems faced by people due to unwanted waste. Microorganisms have amazing metabolic activity as these grow/survive in different environmental circumstances and their nutritional capacity shows the variety in uptake of waste, which make them useful as bioremediators. This chapter includes the types of bioremediations based upon the location and types of contaminants (biosparging, bioaugementation, bioventing, biopiling). It involves the action of microbial agencies like fungi, algae, yeast and bacteria to degrade, eradicate, immobilize or detoxify the harmful organic waste from the surrounding. Phytoremediation and enzyme bioremediation are the other processes involved in bioremediation. The main principle of bioremediation involves the complete conversion of pollutants (hydrocarbons, heavy metals, dyes etc.) into usable substances that depends upon various factors of bioremediation which are described in this chapter. A more advanced technique of gene manipulation of microbial strains is also discussed in later part of the chapter.

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1. Introduction

Bioremediation is a process of recycling unwanted wastes into desirable ones by the use of microorganisms and these can be of use to other organisms (Vidali 2001). The unwanted waste here are organic wastes that include municipal biosolids, remains of crop, animal manures, food processing and industrial wastes. (Edward et al., 2019; Bhat et al., 2018; Hammad et al., 2019; Cookson and John 1995). These wastes are responsible for environmental pollution (Cheremisinoff et al., 2013). The fundamental aim of bioremediation is to eradicate the environmental pollutants from the ecosystem with the help of microbes to restore the ecosystem into its original form (Kumar et al., 2018). The microorganisms are distributed worldwide due to their easily growing nature (Madigan et al., 1997). These microorganisms have anomalous metabolic ability, but these can only help in bioremediation when they are in native environment and show less effect in foreign environment. (Hsiao et al., 2008; Semrau 2011). The native microbial communities that adapted at polluted area (hydrocarbons) degrade the pollutant in lesser time as compared to the microbial communities that are not exposed to the polluted area (Maulin 2017).

Environmental pollution is reduced by the use of microorganisms having ability to convert, modify and utilise toxic and unwanted pollutants as useful energy and biomass producing units (Mata et al., 2010; Verma et al., 2016). Microbial consortium is one of the best methods applied to degrade contaminants from the ecosystem (Das and Chandran 2011). The main biological agents used as bioremediators are archaea (Ebrahimipour et al., 2006), bacteria (Antizar 2010), fungi (Harms et al., 2011), and algae (Zeraatkar 2016). Bioremediation shows better effects than other conventional physicochemical methods such as evaporation, sorption, osmosis etc (Madan et al., 2018) by efficiently removing contaminants even at very low levels and serve as effective pollutant removing tool in soil water and sediments (Coelho et al., 2015; Demnerova et al., 2005). Along with soil pollution, water pollution has also emerged as a burning threat for entire world. The marine environment is mainly polluted by heavy metals which interact with protein and disturb the metabolic pathways of the living organisms which causes their death (Khandaker et al., 2021). According to a report by WHO heavy metals mainly cadmium, chromium, cobalt, copper, lead, nickel, mercury, and zinc are harmful for the whole environment (water, soil, sediments) (Rajesh et al., 2014). Bioremediators or genetically engineered microorganisms (GEMs) have greater potential to degrade pollutants in groundwater, activated sludge, and soil environments. Here in this chapter, we review the role of microorganism in bringing about bioremediation to solve the prevailing environmental threats.

2. Types of Bioremediations

Bioremediation is a field of biotechnology that involves the removal of contaminants, pollutants and toxins from soil, water, and other environments using living organisms such as microorganisms and bacteria. Bioremediation can be applied in two ways, depending on the site of the location, principles of bioremediation used, advantages of the applied method, restrictions or limitation of the bioremediation method used, and potential solutions (Figure 1) (Kensa 2011).

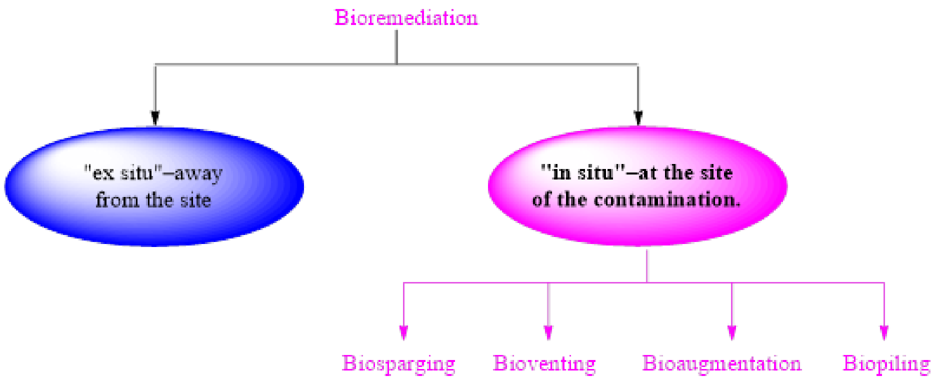

Figure 1. Types of Bioremediations.

2.1. Techniques for *Ex-Situ* Bioremediation

Ex-situ bioremediation refers to waste treatment that takes place away from the actual toxication site, these techniques entail excavating samples and treating them away from contaminated areas, resulting in high costs and environmental disruption. In this process, the contaminants are excavated from the original site and treated in a controlled environment (Tomei and Dugulis 2013). Composting, which is the degradation of organic waste products in the presence of microorganisms typically at elevated temperatures ranging from 55-65°C, is the most common example of *ex-situ* bioremediation (Schuchardt 2005).

2.2. Techniques for *In-Situ* Bioremediation

In-situ bioremediation refers to waste detoxification that takes place at the source of contamination (Haq et al., 2021). It is mostly used to remediate soil and groundwater pollution (Hsia et al., 2021). However, the *in-situ* bioremediation methods are influenced by a number of elements like contamination types, characteristics of location, distribution and concentration of the contaminant, identification of the microbiological community at contamination site's, temperature, pH of the location, nutrient availability etc. (Boopathy 2000; Alvarez et al., 2020).

The above-mentioned variables are only surface-level and unsuitable for in situ bioremediation. Hence, to enhance the pace of breakdown, *in-situ* bioremediation techniques are used, such as aeration, nutrient addition and moisture management. The use of an onsite biological treatment to remove harmful chemicals existing in the environment is known as *in-situ* bioremediation. Some examples of *in-situ* bioremediation techniques are given below.

2.2.1. Biosparging

By injecting air under pressure below the water label, this approach raises ground water oxygen concentrations to improve the rate of biological degradation and volatilization of pollutants with the aid of microorganisms (Johnson et al., 2001).

2.2.2. Bioventing

Bioventing is all about aerating soils to stimulate *in-situ* biological activity which promotes the bioremediation (Lee and Swindoll 1993). By using wells, soil can be directly aerated into residual contamination. Hereafter, as vapours flow gradually through biologically active soil, the adsorbed fuel residuals, as well as other pollutants, undergo biodegradation (Hoeppel et al., 1991).

2.2.3. Bioaugmentation

Bioaugmentation is a bioremediation approach that uses a group of naturally occurring microbial strains or a genetically modified strain to clean contaminated soil or water (Vogel 1996). Generally, it is used to reactivate activated sludge bioreactors in municipal waste water treatment plants (Herrero and Stuckey 2015). This technique can be applied to those locations where the ground water and soil is contaminated with halogenated solvents like tetrachloroethylene, chloroform, dichloromethane, trichloroethylene etc. Microorganism can break down completely these pollutants into their corresponding hydrocarbon and halogens, which are harmless in nature (Liang et al., 2020).

2.2.4. Biopiling

Biopiling is a large-scale method that involves heaping excavated soils into heaps and then bioremediating them under a vigorous aeration condition. Pollutants are then degraded further into CO_2 and water (Germaine et al., 2015). A biopile system consists of a treatment bed, aeration system, irrigation system, and leachate collecting system (Fahnestock et al., 1998). The bioremediation process can be affected by eleven environmental variables. Moisture, heat, nutrients, oxygen, and pH of the site are monitored and regulated to assist biodegradation process (Kumar et al., 2020). The irrigation/nutrient system is installed in such a way that it is hidden beneath the soil, allowing air and nutrients to flow via vacuum or positive pressure.

3. Different Methodologies Involve in Bioremediation

3.1. Microbial-Bioremediation

As illustrated in Figure 2, microorganisms play a very important role in bioremediation. A quick discussion of a few of the categories follows:

a. *Bacteria:* Bacteria are important biosorbents for the treatment of polluted ecosystems (Colleran 1997). These have the capacity to grow under regulated settings while also being able to withstand severe environmental conditions. In contaminated settings, they have high biosorbent activity against heavy metals (Bhakta et al., 2012). Gram-positive bacteria are found to consist of peptididoglycan layers which are made up of glutamic acid, alanine, and teichoic acid (Sizar and Unakal 2020), whereas gram-negative bacteria have glycoproteins, phospholipids, enzymes lipopolysaccharides, lipoproteins as their cell wall components (Beacham 1979). These function as active sites for binding heavy metal ions, resulting in heavy metals being removed from the contaminated environment (Biswas et al., 2021). The microorganisms like *A. ferrooxidans* (DSM 11477) and *A. thiooxidans* (DSM 11478) may be used to effectively remove Cr (VI) (Cabrera et al., 2007). Few bacteria have the ability to remove Ni, Mn, Cu, Cd, and Zn from contaminated environments (Ozdemir et al., 2009). Bioremediation of heavy metals can be effectively done by consortia of bacterial strains over a single strain culture (Mukred et al., 2008).

b. *Fungi:* Fungal degradation and detoxification is termed as mycoremediation (Tomer et al., 2020). Fungi function as effective biocatalysts for heavy metal bioremediation because they can incorporate heavy metals into their mycelium and spores. Their strategy for metal ion bioremediation involves accumulation within cells, extracellular precipitation, and valence transformation. Fungi are, without a doubt, the only creatures on Earth capable of decomposing wood. Marine derived fungi like *Pycnoporus coccineus*, *Phanerochaete chrysosporium* etc. are capable of degrading lignin (Raghukumar et al., 2008). *Rhizopus oryzae* CDBB-H-1877 has the capacity to biosorb pentachlorophenol by chlorination and methylation (Tigini et al., 2009). The fungus from the class zygomycetes and fungi like *Aspergillus sp*. *Penicillium chrysogenum*, *Scedosporium apiospermum*, *Penicillium digitatum*, *Fusarium solani* have the ability to decolorize and detoxify textile waste water by degrading polychlorinated biphenyls (PCBs) (Tigini et al., 2009).

c. *Algae (*cyanoremediation*):* Algae has long been known to be highly effective in the bioaccumulation of heavy metals and the breakdown of xenobiotics (Suresh and Ravishankar 2004). They play an important role in carbon dioxide fixation and are a valuable biomass for biofuel generation, thus the bioremediation process including algae has aroused researchers' interest throughout the years (Yun et al., 1997). Algae *like Selenastrum capricornutum* and *Monoraphidium braunii* have shown the potential for the removal of bisphenol, benzene, toluene, and naphthalene from contaminated environments (Cooke and Mouradov 2015).

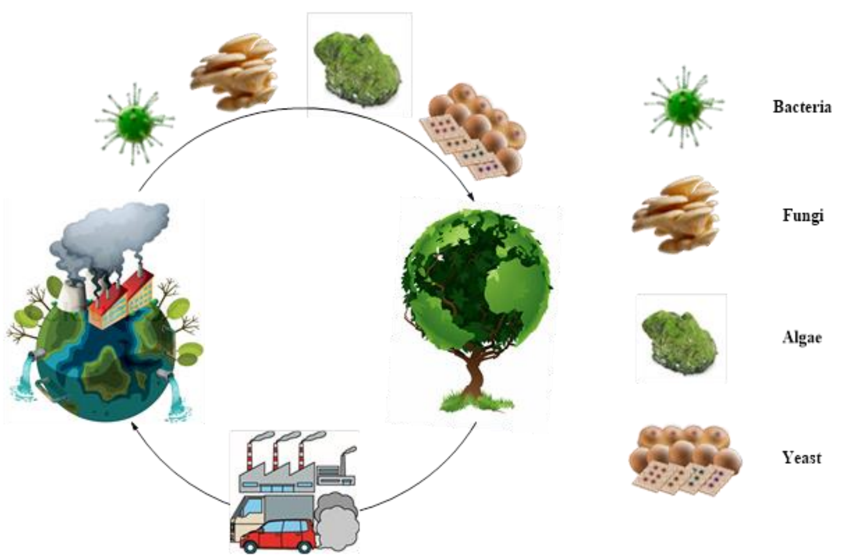

Figure 2. Microbial- bioremediation.

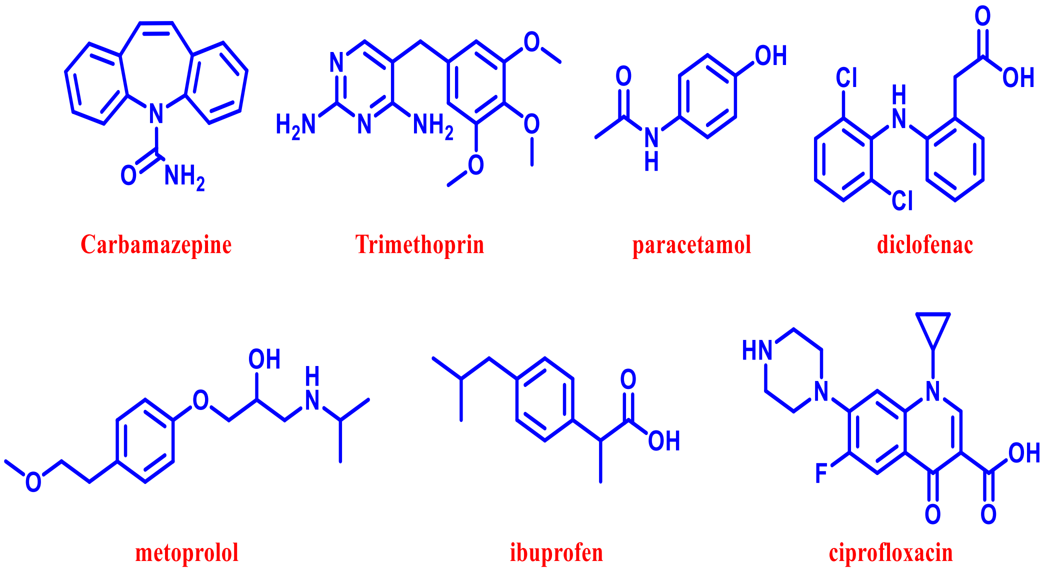

Figure 3. Pharmaceutical Contaminants.

Microalgae are capable of bioadsorbing organic and pharmaceutical contaminants (Hena et al., 2020). Algae species like *Chlorella sorokiniana*, *Nannochloris sp., and Chlamydomonas mexicana* have a vital role in bioremediation. The bioremediation of diclofenac, ibuprofen, paracetamol, metoprolol, carbamazepine, trimethoprim, ciprofloxacin, triclosan can be done by few species of algae, of which some of the structures are in Figure 3 (Gavrilescu et al., 2015; Joseph and Ketheesan 2020).

d. *Yeast:* Yeasts can tolerate a broad range of environmental conditions (Deak 2006) and survive in in temperature between 0-50ºC. The use of yeast may be a better alternative for removal of contaminants (heavy metals) by bioremediation technique (Abbas and Badr 2015). Yeast cell walls have a negative charge on their surface and thus they because of electrostatic attraction these bind with heavy metal cations. (Eddy and Rudin 1958; Fukudome et al., 2002). The heavy metals such as Cr, Pb, Zn, Hg, Cd, and Ni are usually removed by yeast Saccharomyces cerevisiae through bioremediation (Ozer and Ozer 2003; Mapolelo and Torto 2005). Candida tropicalis, Candida utilis, and Cyberlindnera fabianii, in addition to Saccharomyces cerevisiae, have been identified as bioremediators of contaminated environments.

3.2. Phytoremediation

The use of plants and associated organisms to remove the contaminants from air, soil and water is referred as phytoremediation (Salt et al., 1998). Both heavy metals and organic contaminants can be removed by this method (Ali et al., 2013). A range of physical features of plants and plant activities help in the clean-up of polluted areas in phytoremediation. It is a low-cost, high-impact, and environmentally friendly *in-situ* remediation technique that is powered by solar energy. Phytoremediation involves processes like phytoextraction, phytofiltration, phytostabilization, phytovolatilization, phytodegradation etc. (Figure 4) (Romdhane et al., 2021).

Phytoextraction is a subprocess of phytoremediation in which the contaminants are absorbed by plant roots from the soil or water. These heavy metals pollutants then are translocated to shoots (biomass accumulated here) (Yan et al., 2016). For successful and optimal phytoextraction it is essential biochemical step to translocate metal in the shoots (Page et al., 2006). The second step is phytofiltration which consists of rhizofiltration i.e., absorption of contaminants or pollutants into plant roots that are in solution surrounding the root zone (rhizosphere) (Dushenkov et al., 1995), blastofiltration i.e., using seedlings and caulofiltration i.e., use of leaves and excised plant shoots (Sekara et al., 2005). The mobility of the metals absorbed by these processes in subterranean water is reduced (Etim 2012). The process of reducing the mobility of heavy metal into soil is referred as phytostabilization. Reducing the bioavailability and mobility of metal ions into soil or water or environment or food chain is the fundamental aim of phytostabilization (Shackira and Puthur 2019).

Plants immobilise heavy metals in soils by root sorption, precipitation, complex formation, or rhizosphere metal valence reduction (Erakhrumen and Agbontalor 2007). To degrade organic pollutants, plants usually use the enzymes (independent on rhizospheric bacteria) like oxygenase and dehalogenase (Poschenrieder and Barcelo 2003). Under the process of phytovolatilization, plants convert the absorbed metals into volatile forms and later on these are released by plants into the atmosphere (Awa and Hadibarata 2020). This method is widely applicable for the removal of heavy metals (volatile) like mercury and selenium from the contaminated soil (Vishnoi and Srivastava 2007). Instead of complete removal of pollutants, it just transfers the contaminant from one medium to another i.e., from soil to atmosphere. These pollutants again enter from atmosphere to soil and water. This method has attracted the attention due to its efficacy and cost effectiveness (Karami and Shamsuddin 2010).

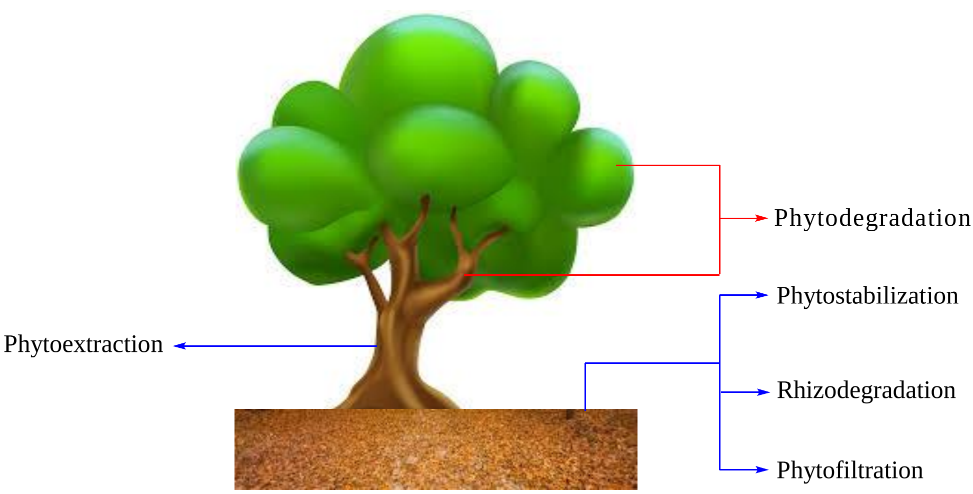

Figure 4. Phytoremedation.

The hyperaccumulation necessities varies with concentration of the metal, ranging from 100 mg/kg dry mass for Cd to 1000 mg/kg for Cu, Co, Cr, and Pb. These data illustrate the shoot-to-soil metal concentration ratio, and the bioaccumulation factor is >1 (Ahemad 2019). When it was compared with other plants, the hyperaccumulators were found to have higher metal tolerance and accumulating ability (Baker et al., 1994). Many plants have been utilized for the phytoremediation of Arsenic and Mercury (Visoottiviseth et al., 2002; Marrugo-Negrete et al., 2015). Different plants have been reported for remediation of heavy metals (Table 1). However, hyperaccumulators have challenges like locating heavy metal, sluggish development, and reduced biomass output etc. It is concluded that this process is time consuming and not applicable for quick treatment of sewage or contaminated areas (Wei et al. 2005). On other hand there are many different rhizospheric microbes that are known to play important roles in plant development and metal tolerance with specific mechanism (Nihorimbere et al., 2011; Mishra et al., 2017). The suitable multifunctional microbial combination from the rhizosphere such as arbuscular mycorrhizal fungi and plant growth-promoting rhizobacteria can be chosen with the help of these information for the creation of a phytoremediation strategy (Requena et al., 1997). It is well known that the main part of phytoremediation is rhizosphere's remediation (Wei et al., 2003). It is very fundamental theory which is applied for the removal of contaminants through combined action of microorganism and plant (Kuiper et al., 2004).

Table 1. Phytoremediation of heavy metals by plants

S. No.	Bioremediation of heavy metals	Phytoremediation by reported plant
01.	Cd	*Pistia stratiotes* (Das et al., 2014)
02.	Pb	*Tagetes minuta and Bidens Pilosa* (Salazar and Pignata 2014)
03.	Zn	*Brassica* (Ebbs et al., 1997)
04.	Cu	*Hirschfeldia incana and Sedum sediforme* (Poschenrieder et al. 2001)
05.	Ni	*Alyssum bertolonii* (Robinson et al., 1997)
06.	Hg	*Brassica juncea* (Raj et al., 2020)
07.	Se	*Brassica* (Banuelos et al., 1997)
08.	As	*Pityrogramma calomelanos, Pteris vittata, Mimosa pudica, and Melastoma malabrathricum* (Mahmud et al., 2008)
09.	Co	*Berkheya coddii* (Keeling et al., 2003)
10.	Cr	*Cyprus papyrus* (Kassaye et al., 2017)

3.3. Enzymatic Bioremediation

The degradation of pollutants by microorganisms is a long process which limits the viability of bioremediation in practice (Ghosh et al., 2017). To address the various constraints, rather than the entire microbe, microbial enzymes isolated from their cells have been utilised for bioremediation (Thatoi et al., 2014). Enzymes are large, complex biological macromolecules that serve as catalysts in a variety of biochemical processes involved in pollution breakdown (Kalogerakis et al., 2017). By reducing the activation energy of molecules, enzymes can speed up a process. Enzymes can be classified into the following categories based on their biodegradation capabilities, as shown in Figure 5.

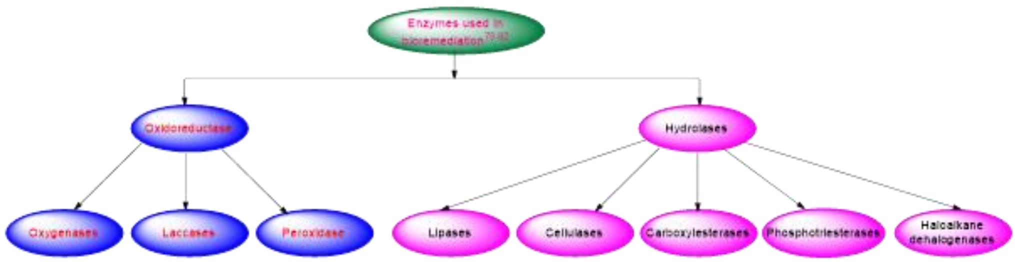

Figure 5. Enzymes involved in bioremediation and their functions.

3.3.1. Oxidoreductases

Oxidoreductases are secreted by various bacteria, fungi, and higher plants to detoxify substances by oxidative coupling. The process involves electron transfer from reductants to oxidants resulting in chloride ions, CO_2 and methanol. The energy or heat released during the breakdown of contaminants by enzyme is used by the microorganisms for metabolism (Khare and Prakash 2017). Oxidoreductases degrades natural and synthetic contaminants (Alneyadi et al., 2018). A Gram-positive bacterium (*Bacillus safensis* CFA-06) produces oxidoreductase which helps in the breakdown of petroleum molecules (Nyika 2021). In nature, a variety of phenolic chemicals are produced by lignin breakdown. The oxidoreductases polymerize these chemicals into different forms (Husain 2006). Various oxidoreductases enzymes like peroxidases and laccase, breakdown the dyes and pigments produced by textile industries. (Novotný et al., 2004).

a. *Oxygenases*: Oxygenases is a very important enzyme. It inserts one or two oxygen atoms in aromatic ring and degrades aromatic compounds via aerobic process. On the basis of oxygen atom involved, oxygenase is classified into two classes i.e., monooxygenase (addition of one oxygen takes place during catalysis) and dioxygenase (addition of two oxygens takes place during catalysis). A pesticide bioremediation enzyme derived from the bacteria *Pseudomonas sp.*, is called as Glyphosate oxidase (GOX). Glyphosate is converted to aminomethylphosphonate (AMPA) by GOX, and then releases the keto acid glyoxylate (Scott et al., 2008). The reactivity and solubility of halogenated compounds is usually enhanced by adding an oxygen molecule and thus by applying this mechanism oxygenases degrade a wide range of substrates, along with halogenated compounds. The compounds employed as co-factor are FAD/NADH/NADPH for oxygenase action. The dehalogenation process can be catalysed for a wide range of substrate like halogen-containing weedkillers, antifungals, and insect killer chemicals by the oxidase. Oxygenase enzyme is also produced by some of the marine bacteria, which helps in the degradation of the organic contaminants (Sivaperumal et al., 2017).
b. *Laccases:* Laccases are the copper-based enzymes which catalyse the oxidation of aromatic compounds like phenols which are found in soil and water. Laccases exist in different isoforms and are generated by bacteria, fungi, insects, plants etc. The laccases may also get released extracellularly, after continuous generation in cell. Ortho and para diphenols, amino-phenols, lignin, and aryl-diamines can be degraded by laccases (Mai et al., 2000, Legerská et al., 2016). Laccases can decolorize azo

dyes very quickly by oxidising their bonds and converting them into less hazardous forms (Rodriguez et al., 1999).

The fungi *Trametes hispida* (Strong and Claus 2011) produces different type of laccases, among them two isoenzymes were isolated. These two isoenzymes are responsible for decolorization. Biotransform phenolic substances can be degraded by the *R. practicola* laccase (Dodor et al., 2004). The protease resistance, stability and half-life of laccases can be improved by immobilization on solid supports (Chakroun et al., 2010). Laccase was immobilised on porous glass beads after being isolated from the fungus *Trametes versicolor*. It is an effective enzyme for bioremediation of a variety of contaminants, including phenolic chemicals, aromatic heterocyclic compounds, and amine-containing aromatic compounds. Laccase can remove electrons from the organic substrate and decrease polluting dioxygen molecules into water (Scott et al., 2008). Synthetic laccase was also utilised in the paper and pulp industries to increase pulp and textile bleaching (Suresh et al., 2008). Laccase X-ray crystal structures deposited in the Protein Data Bank (PDB) were employed in docking investigations with two-dimensional contaminants retrieved from the NCBI database. CORINA, an online tool, was utilised to convert two-dimensional pollution structures into three-dimensional structures. GOLD was also utilised to dock protein-ligand interactions. The best average GOLD fitness score among selected datasets for laccases produced by bacteria and fungi was about 30-17%, i.e., these contaminants can be oxidised by these laccases (Bansal and Kanwar 2013).

c. *Peroxidases:* Peroxidases are found in all living things, including animals, plants, fungus, and bacteria. Peroxidases use hydrogen peroxide and a mediator to aid in the breakdown of lignin and other aromatic contaminants. Phenolic radicals, which are formed by the oxidation of phenolic substances, congregate and become less soluble, causing them to precipitate quickly. The enzyme may or may not contain Heme. (Koua et al., 2009) Peroxidases that contain heme can be split into two classes: One category is unique to animals, whereas the other is present in fungi, bacteria, and plants. There are three types of peroxidases found in bacteria, fungus, and plants: intracellular enzymes found in class 1 are, cytochrome-c peroxidase (produced by yeast), ascorbate peroxidase i.e., APX (produced by few plant species) and bacterial catalase peroxidases. Enzymes in class 2 are the Lignin peroxidase (LiP) and manganese peroxidase, which are produced by fungi. Peroxides (MnP) secreted by plants like horseradish peroxidases (HRP) (produced by horseradish plants) are found in class 3. The non-heme peroxidases from five different families are thiol peroxidase, alkylhydro-peroxidase, halo-peroxidase, manganese-catalase, and NADH-peroxidase (Bilal et al., 2017). Among the observed peroxidases, lignin peroxidase and manganese peroxidase are the most powerful enzymes for the degradation of harmful compounds. Horseradish peroxidases-immobilized cross-linked enzyme aggregates (HRP-CLEAs) were produced by the use of cross-linkers like ethylene glycol-bis [succinic acid N-hydroxy succinimide, (EG-NHS)]. The biodegradation efficiency of HRP-CLEAs was explored by introducing a packed bed reactor system (Sumithran et al., 2012). Oxidative para-dechlorination of hazardous pollutant and carcinogen 2,4,6-trichlorophenol can be done by HRP successfully

(Alneyadi and Ashraf 2016). Soybean peroxidase and chloroperoxidase are capable of degrading thiazole compounds (Karigar and Rao 2011).

3.3.2. Hydrolases

Hydrolytic enzymes are most typically utilised for pesticide and insecticide bioremediation and toxicity reduction. (Sharma et al., 2018) The mechanism of action of different hydrolytic enzymes takes place via cleavage of bonds such as esters, peptides, carbon-halogen bonds etc. Physico-chemical therapy is quite expensive as compared to enzymatic bioremediation of hazardous chemical compounds therefore breakdown of hazardous organic molecule is preferred (Karigar and Rao 2011). The bioremediation of organic polymers, hazardous chemicals with molecular weights (less than 600 Da, i.e., that may pass through cell pores) can be done by hydrolase (microbes produce extracellularly) (Sánchez-Porro et al., 2003). The use of hydrolytic enzyme in bioremediation of oil spills, organophosphate, and carbamate pesticides is extremely successful. Proteases, lipases, xylanases, DNAses, and amylase are extracellular hydrolytic enzymes utilised in the food and chemical industries. The enzymes hemicellulase, cellulase, and glycosidase are utilised to degrade biomass (Su et al., 2017). Recently, Lei et al., extracted the carbendazim hydrolyzing enzyme gene from *Microbacterium sp.* djl-6F, which was cloned into *E. coli* BL21 (DE3) to enhance the secretion of enzyme. Carbendazim was hydrolyzed into 2- aminobenzimidazole by this enzyme. Another study connected the organophosphorus hydrolase enzyme to Gram negative bacteria's outer membrane vesicles, which showed great activity for the breakdown of parathion chemical compounds (Shukla and Gupta 2007).

a. *Lipases:* Lipases are found all over the world and catalyse the conversion of triacylglycerols to glycerol and free fatty acids, both of which are important components of hydrocarbons. Many types of bacteria, plants, actinomycetes, and mammalian cells generate lipases. (Prasad and Manjunath 2011) Inter-esterification, esterification, alcoholics, hydrolysis, and aminolysis processes can be performed by the Lipases (Ghafil et al., 2016). The concentration of hydrocarbons in the contaminated soil can be decreased by the Lipase activity. These enzymes hydrolysed fatty acids into triglycerol, diacylglycerol, monoacylglycerol etc (Verma et al., 2012). To improve the secretion of the microbial lipases, various statistical tools were used for the optimisation of the medium. (Yang et al., 2017).
b. *Cellulases:* Cellulases are enzymes that break down cellulose, the most common biopolymer on the planet. Microorganisms can generate cellulase that is cell-bound, linked with the cell envelope (Karigar and Rao 2011). For bioremediation of ink during paper recycling in the paper and pulp industry, cellulases have been used (Annamalai et al., 2016). Since alkaline cellulases generated by marine microbes are more suitable for severe industrial processes in industries such as food, textile, laundry, pulp and paper, biofuel generation, etc, therefore cellulases attracted scientists. (Khan et al., 2016 and Imran et al., 2016) *Humicola species*'*s* cellulase can tolerate the adverse environmental conditions such as wide range of pH and temperature. (Cummins et al., 2007) This is very useful to cleave the weak bonds such as hydrogen bonds in detergents and washing powders. (Yin et al., 2016)
c. *Carboxylesterases:* Carboxylesterases are enzymes that catalyse the degradation of manufactured and natural products such as organophosphates, carbamate ester bonds,

and chlorine-containing organic compounds (Heidari et al., 2005). Pesticides, insecticides, and fungicide spray have all been degraded using carboxylesterases in the field. On the outer membrane of *E. coli* 117 the enzyme carboxylesterases E2 was shown (from the *Pseudomonas aeruginosa* PA1 strain) for mercury absorption in the contaminated location. Synthetic pyrethroids, a significant family of insecticides, have been employed in the fields for the past 40 years. Carboxylesterases hydrolyze their ester linkage, which is a common route for the breakdown of all kinds of pyrethroid insecticides. The active site of enzyme obtained from *Lucilia cuprina* carboxylesterases was tuned for the hydrolysis of pyrethroids through the process of vitro mutagenesis (Scott et al.,2008) *L. cuprina* carboxylesterases E3 are responsible for the breakdown of organophosphorous pesticides (Romeh and Hendawi 2014).

d. *Phosphotriesterases:* Phosphotriesterases may decompose chemical waste from companies as well as pesticides used in agriculture fields like parathion (Gao et al., 2014). Parathion, an organophosphate-containing compound, is found in herbicides and insecticides (Restaino et al., 2016). The gene of SsoPox W263F and SsoPox C258L/I261F/ W263A, has been obtained from the wild type *Sulfolobus solfataricus*, and SacPox. It was accessed from *Sulfolobus acidocaldarius*, which were further produced and purified (Yamaguchi et al., 2016). The examples of marine bacteria are *Phaeobacter sp.*, *Ruegeria mobilis*, and *Thalassospira tepidiphila* which are used for the degradation of the phosphate triester found around coastal areas of oceanic environments *(*Koudelakova et al., 2013).

e. *Haloalkane dehalogenases:* The polluted soil contains synthetic and natural organohalogen compounds which are harmful (Kotik and Famerova 2012). Haloalkane dehalogenases generate alcohol and halides by hydrolyzing the carbon halogen bond seen in different halogen-containing contaminants (Pavlova et al., 2007). Haloalkane dehalogenase's active site is sandwiched between two domains. An eight-stranded b-sheet is encircled by a-helices in the enzyme's primary domain (Nagata et al., 2015). In the bacteria *Xanthobacter autotrophicus*, the first haloalkane dehalogenase was found. GJ10 is capable of degrading 1,2-dichloroethane (Poelarends and Whitman 2010). Following that, numerous dehalogenases from Gram positive and Gram negative haloalkane degrading bacteria were cloned and described. The dsp is a digital signal processor. An artificially gene was produced and expressed in the purple sea (California) urchin Strongylocentrotus purpuratus, according to the sequence deposited in the NCBI Protein database under accession number XP 794172. It was the first non-microbially manufactured dehalogenase enzyme (Fantroussi and Agathos 2005).

4. Factor Affecting Bioremediation

Bioremediation is an alternative that suggests the leeway to dispose or reduce various toxins by the use of natural biological activity. As such, it uses relatively low-cost, low-technology techniques. Microbes exploit the different contaminants or pollutants for the production of energy and nutrients to generate more cells (Weyens et al., 2009). The rate of degradation of contaminant is affected by the improper contact of bacteria and pollutants moreover uneven distribution of microbes and contaminants in the environment. The factors affecting the efficiency of bioremediation depends on the nature and quantity of toxins, capability of contagious population that degrades the pollutants, the physicochemical features of the environment like, the type of soil, temperature, pH, availability of the oxygen and other nutrients (Fantroussi and Agathos 2005). Microorganisms show amazing metabolic activities for the appropriate bioremediation technique (Singh et al., 2020). Most of the pollutants that gets adsorbed in the soil may transformed into less or more toxic substances by the action of microbes like conversion of Trichloroethylene into more toxic Trichloroacetic acid (Afzal et al., 2014) Microbial communities (endophytes) having significant metabolic (anabolic and catabolic) activity takes major role in the degradation process (Gupta 2020). There are various factors involved to increase the rate of bioremediation (Guthrie 1998). As microbial cells are responsible for metabolising the pollutants adsorbed in the soil, so their growth rates depend upon biological (biotic) and physicochemical (abiotic) parameters. (Boopathy, 2000). The major factor upon which the bioremediation depends are given below (Srivastava et al., 2014).

4.1. Biotic Conditions

The degradation of pollutants (organic compounds) is more highly achieved by the bacterial chemotaxis (Pandey and Jain 2002). The rate of bioremediation or degradation of contaminants depends upon the biomass chemical composition and varies from species to species (Gadd 2009). Different types of species like bacteria, algae, fungi and yeast have different biosorbent metal properties (Das et al., 2008). The major biotic factors that alter the rate of contaminant degradation are: Tolerance Capacity (Hu et al., 2001), concentration of biomass, (Monteiro et al., 2012) horizontal gene transfer, enzyme action, genetic mutation, interaction of microorganisms with the pollutant (competition, succession and predation) and its own growth rate (Naik and Duraphe 2012).

4.2. Environmental or Climatic Conditions

In real sense a fruitful interaction among the microbes and targeted toxin depends upon the various ecological conditions at the spot of interaction (D'Souza et al., 2018). The activity and growth of bioremediators are affected by various environmental factors like availability of nutrients, temperature, pH, water solubility, soil structure, moisture, redox potential and oxygen contents, bioavailability of contaminants, less knowledge of this field etc. (Naik and Duraphe 2012). All the above factors determine the kinetics of the contaminant degradation (Adams et al., 2015). Few among the above-mentioned factors are discussed in detail:

4.2.1. Temperature

Temperature is one of the utmost thermodynamic variables on which the existence of microorganisms and composition of pollutant depends. (Das and Chandran 2011). The bioremediation process slows down in cold environments such as the Arctic. Reason behind the slow biodegradation is the shutdown of microbial channels or freezing of entire cytoplasm which makes most oleophilic microbes metabolically inactive (Macaulay 2015; Si-Zhong et al., 2009). Every biological enzyme needs optimum temperature to degrade any pollutant andshows inactivity in every temperature. Thus, the maximum degradation takes place at optimum temperature and it may increase, decrease or decline in any other temperature.

4.2.2. Moisture, pH, Concentration of Oxygen and Soil Structure

The activity and growth of microorganisms are readily affected by pH, moisture, concentration of oxygen and soil structure (Naik and Duraphe 2021). For maximum growth and activity microorganisms require adequate water. If there is deviation from optimum soil moisture content, then biodegradation rate gets changed.

The rate of removal of pollutant also depends upon the pH of compound, different pH (acidic, basic, alkaline) has different impact on microbial metabolic activity (Asira 2013). The higher or lower pH value shows precise change in metabolic processes of microbes (Wang et al., 2011). The pH from 6.5 to 8.5 is optimal pH for degradation of most aquatic and terrestrial communities (Cases et al., 2005).

Availability of oxygen is another physical factor that determine the attack of microbes over the particular contaminant. Some microorganism (aerobic) requires oxygen to grow and work while other (anaerobic) can function even in the absence of oxygen. The biotic degradation can be performed in both conditions. The pollutant having hydrocarbons work in aerobic conditions while chlorinated compounds degrade only in anaerobic conditions. (Macaulay 2015; Si-Zhong et al., 2009). For optimal aerobic conditions the oxygen is added by introducing hydrogen peroxide or magnesium peroxide in the ecosystem.

The effective delivery of water, nutrients and air totally depends upon the soil structure. If the soil is less permeable it retards the movement of water, nutrients and oxygen which lowers the chance of in situ clean-up techniques. To improve the soil structure, materials such as gypsum or organic matter can be used.

5. Microorganisms and Pollutants

Industrialisation and various other human activities led to environmental pollution that is affecting the whole human race. The novel technologies should be designed for the protection of humans and environment from these hazardous contaminants. Bioremediation is one among these methods (Raghunandan et al., 2018; Raghunandan et al., 2014). In bioremediation, the toxic heavy metals are used by microbes as a source of nutrition. Few metals e.g., Ni, Cu, Fe and As are useful for human body when consumed in limited amount, but are vastly toxic when taken in higher concentration (Valko et al., 2016). To make the soil free from hazardous heavy metals microbes are used. They accumulate the metal inside them and degrade the contaminant and thus decrease environmental pollution. Some microorganisms are mentioned in the Table 2 that help in degrading xenobiotics.

Table 2. Microbes help in degrading various xenobiotics (harmful chemical)

Microorganisms	Xenobiotics
Methosinus sp. (Udebuani et al., 2012)	PCBs and formaldehyde etc.
Corynebacterium (Verma and Kuila 2019)	Aromatic compounds and hydrocarbons etc.
Flavobacterium (Verma and Kuila 2019)	Naphthalene, aromatics, biphenyls etc.
Methanogens (Verma and Kuila 2019)	Biphenyl, PCBs, polycyclic aromatic compounds etc.
Nocardia sp. (Verma and Kuila 2019)	Phenoxyacetate, halogenated hydrocarbon diazinon etc.
Arthrobacter sp. (Verma and Kuila 2019)	Benzene, long chain alkanes, hydrocarbons, phenoxyacetate, cresol, pentachlorophenol, polycyclic aromatic, phenol etc.
Mycobacterium sp. (Park et al., 1998)	polycyclic hydrocarbons including aromatic and aliphatic hydrocarbons etc.
Alcaligenes sp. (Kapley et al., 1999)	alkylbenzene sulfonates, Halogenated hydrocarbons etc.
Rhodococcus sp. (Dean-Ross et al., 2002)	Aromatics and aliphatic hydrocarbons
Pseudomonas (Cybulski et al., 2003)	Anthracene, benzene, hydrocarbons, PCBs etc
Bacillus sp. (Cybulski et al., 2003)	Halogenated hydrocarbons, phenoxyacetate etc.

6. Genetic Engineering of Microorganism for Enhanced Bioremediation

Genetic engineering is the branch of biotechnology that deals with the gene manipulation. Microbial strains those are effective against various pollutant are become more potent by doing gene manipulation through genetic engineering (Recombinant DNA technology) (Micklos et al., 1990). These microorganisms are termed as GMM (genetically modified microbes) or GEM (genetically engineered microorganisms). GEMs are effective in soil activated sludge and groundwater bioremediation. Some of the GEMs are useful in the degradation of the heavy metals (Verma and Kuila 2019).

Table 3. Bioremediation of heavy metals by genetically engineered microbes

Microbes	Heavy metals
Deinococcus radiodurans (Brim et al., 2000) *E. coli* strain (Murtaza et al., 2002) *Achromobacter* sp. AO22 (Ng et al., 2009) Pseudomonas K-62 (Kiyono et al., 2006) *E. coli* JM109 (Zhao et al., 2005) *Acidithiobacillus ferrooxidans* (Sasaki et al., 2005)	Hg
P. fluorescens 4F39 (López et al., 2002) E. coli SE5000 (Deng et al., 2005)	Ni
Escherichia coli and *Moraxella* sp.) (Bae et al., 2003)	Hg & Cd
Mesorhizobium huakuii B3 (Sriprang et al., 2003) Caulobacter crescentus JS4022/ p723–6H (Patel et al.,2010) E. coli strain (Kang et al., 2007)	Cd2+
E. coli (Kostal et al., 2004) *Asphingomonas desiccabilis* and *Bacillus idriensis* strains (Liu et al., 2011)	As
E. coli strain (Freeman et al., 2005)	Ni & Co
Escherichia coli MC1061; *Bacillus subtilis* BR151; *Staphylococcus aureus* RN4220 (Bondarenko et al., 2008)	Cd, Pb, Hg, Zn,
B. subtilis BR151 (pTOO24) (Ivask et al., 2011)	Cd

Conclusion

Bioremediation is a very valuable technique used for degrading, cleaning, managing and recovering the harmful organic waste by the action of microorganisms. Itis usually performed by two methods i.e., *in-situ* and *ex-situ*. Depending upon the disposal of waste, the degradation of toxins which are exaggerated by various factors such as temperature, aeration, moisture, availability of nutrients and oxygen soil structure and moreover the competition among microbial consortium either *in-situ* or *ex-situ* can be applied for bioremediation. Based on these factors, degradation is effective only when all the conditions allow microbial growth and activity. Bioremediators also accumulate the heavy metals for nutrients and makes the environment clean. By performing various modifications in gene through recombinant DNA technology, the microorganism works more effectively and function in more than one way.

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Chapter 9

AGRICULTURE WASTE TO VALUE ADDED PRODUCTS CONVERSION TECHNOLOGY: PRESENT, PAST AND FUTURE

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ABSTRACT

As the human population grows the aspiration to meet high standards of life is putting enormous pressure on natural resources with negative impact on the environment. To achieve the goal of sustainable development it is important to adopt eco-friendly measures in all anthropogenic activities. The eco-friendly measures amount to reducing ecological footprint which is a metric used to quantify usage of natural resources and generation of waste versus the capacity of nature to absorb this waste and regenerate the used resources. The best way forward to minimize ecological footprint is to efficiently manage our waste. The agriculture sector is beyond doubt the largest anthropogenic activity covering nearly 12% of global land area. Every year nearly billion metric tonnes of agriculture waste is generated. It is unfortunate that a significant proportion of this waste is being burnt contributing towards CO_2 emissions when on a contrary this waste is in fact an abundant cheap source of biomass which could be put to use to meet the renewable energy requirements. The production of biofuel from maize and sugarcane is now well-established. Currently considerable efforts are being put into developing an economically viable technology of converting lignocellulosic matter into the same. There are number of other applications to which agricultural waste could be put to use. As for example using lignocellulosic content as raw material for the production of bioactive compounds, use of rice hull and nut waste as reinforcement additive in polymer materials and biodegradable packaging while coconut shell, tea waste, bran, straw, and garlic peel can be used as efficient adsorbents for removal of water contaminants like dyes,

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pesticides, industrial solvents, pharmaceutical organic compounds and heavy metals. The agriculture waste can also be used to maintain the fertility of soil. These applications present the best examples of bioeconomy. In this chapter, a concise review stressing on the need of bioeconomy is presented highlighting the various value-added products obtained from agricultural waste with a brief discussion into the methods and technologies used.

1. INTRODUCTION

The limited availability of natural resources has forced humankind to look for sustainable ways to support its economic growth. In the past 10 years there has been a manifold increase in developing methods and technologies to convert waste into value-added products. Now waste is regarded as a valuable resource. The agriculture sector being the largest anthropogenic activity generates highest amount of biomass waste (European Commission, 2015). As per annual global estimates agricultural waste constitutes nearly 75% of lignocellulosic biomass waste (Gupta and Verma, 2015). The global generation of lignocellulosic biomass residue is put up at 200 X 10^9 tons/year (Pattanaik et al., 2019). The agricultural waste mainly consists of crop residues, agro-industrial waste, livestock waste, and waste of fruits/vegetables. The straw, husk, shell, leaves, cob, and stover are main forms of on-field crop residues. The residue-to-crop ratio (RTC) indicates the amount of residue (waste) generated to the amount of main product of the crop (Maltsoglou et al., 2014; Manual, FAO United Nations, 2014). Table1 presents RTC for major crops cultivated worldwide. The global production of main crops in year 2018 (States, 2021) is tabulated as in Table 2. From data analysis of Tables 1 and 2 the main crops generating large amount of crop residues are maize (corn), wheat, oilseed, rice, cotton, and soybean. The waste produced at industries based on agricultural sector constitutes agro-industrial waste. The main agro-industrial waste comes from sugarcane industry (180.73 million tons annually), edible oil industry (35.19 million tons from palm-oil industry alone), and food-processing industries. The third category of agricultural waste is livestock waste which consists of liquid/solid manure and field wastewater (Pattanaik et al., 2019). If discharged untreated this liquid waste being rich in nitrogen and phosphorus content can potentially act as surface water pollutant. The last category consists of waste of fruits/vegetables coming from household, farm-markets, and food-processing industries. The fruit/vegetable waste is nearly 25-30% of their total production. For some fruits like orange, mango, lemon, and pineapple the waste can be as high as 60% (Joshi and Sharma, 2011; Singh et al., 2020). Therefore the problem of its disposal is a big challenge for food-processing industries as well as local municipality bodies.

The agricultural waste is high in nutritional value and presents great potential of being harnessed to yield other value-added products like biofertilizers, biofuels, animal fodder, fine chemicals etc. (Sadh et al., 2018). On the other hand if this waste is left untreated it has adverse environmental impacts like adding greenhouse gases to environment, huge landfills, and a source of air/water pollution. The practice of burning leftover crop-residues on field releases large quantities of greenhouse gases in a quite short time-period adversely affecting the local air quality and disrupting rainfall patterns (Andini et al., 2018). In India estimates indicate that on an average 92.81 million metric ton of agriculture waste is burnt (Directorate, 2012-13). The burning also results in the loss of nutrients present in crop residues which otherwise would have enriched the soil. Burning kills beneficial soil organisms which negatively impacts nitrogen and carbon content in top 0-15 cm of soil profile. This very region of soil is important for crop growth (Directorate, 2012-13).

Table 1. Average residue-to-crop ratio for major agricultural crops (Maltsoglou et al., 2014; Manual, FAO United Nations, 2014)

Crop	Residue-to-crop ratio for different residues
Barley	1.35 (Straw)
Coconut	0.47 (Fronds), 0.49 (Husk), 0.39 (Shell)
Coffee	1.32 (Husk)
Cotton	0.26 (Hull), 3.40 (Stalk)
Groundnut	0.47 (Husk)
Maize (Corn)	0.33 (Cob), 0.22 (Husk), 1.96 (Stover)
Oil palm	0.31 (Empty bunches), 2.60 (Fronds), 0.06 (Shell)
Millet	2.54 (Straw)
Oat	1.42 (Straw)
Rice	1.33 (Straw), 0.25 (Husk)
Rye	1.61 (Straw)
Sorghum	2.44 (Straw/Stalk)
Soybean	1.53 (Straw), 1.09 (Pods)
Sugarcane	0.20 (Tops/Leaves), 0.26 (Baggase)
Wheat	1.28 (Straw)

Table 2. World-wide data for the production of major crops for the year 2018-19 (States, 2021)

Crop	Total production (Million metric tonne)
Barley	139.42
Cotton	118.56
Groundnut	46.81
Oilseed	600.04
Maize	1123.84
Sorghum	59.24
Soybean	361.04
Rice	497.32
Wheat	730.90

The loss of agricultural waste either due to burning or landfills is a substantial economic loss. The policy makers around the world have gradually come to realize the potential of agricultural waste as a resource. The subsequent sections of this chapter will present examples on how this waste can be turned into a resource. Here it is important to mention that the focus of contemporary governments is to shift from a linear economy model to a circular economy model which will present a solution to waste-disposal problems and subsequently this shift will enable the resolution of environmental issues without compromising the current pace of economic growth.

2. Circular Economy Model

The current global economy is fossil-fuel driven and follows a linear economy model. The linear economy model is based on resource extraction, manufacturing, use, and disposal at the end of the life-cycle of products. The problem with this model lies in an inefficient use of resources, as once the resources are disposed off at the end of products' life-cycle no efforts are put in to re-extract any remaining valuable resources. Basically this model is consumerism-oriented and intrinsically wasteful. Traditionally cultures across the world have always focused on using resources judiciously with an aim to minimize waste generation. This is exactly the mantra of a circular economy model. The whole purpose of circular economy model is efficient resource management (Borrello et al., 2016; Cantzler et al., 2020; Duque-Acevedo et al., 2020; Mohan et al., 2018). In European Union circular economy is defined as an, "economy that is, restorative or regenerative by intention and design and that aims to maintain the value of products, materials, and resources for as long as possible by returning them into the product cycle at the end of their use while minimizing the generation of waste" (European Environmental Agency, 2018). Here the emphasis is on repair, reuse, refurbishment, and recycling. Figure 1 highlights the different approaches followed by linear economy and circular economy (CE) models.

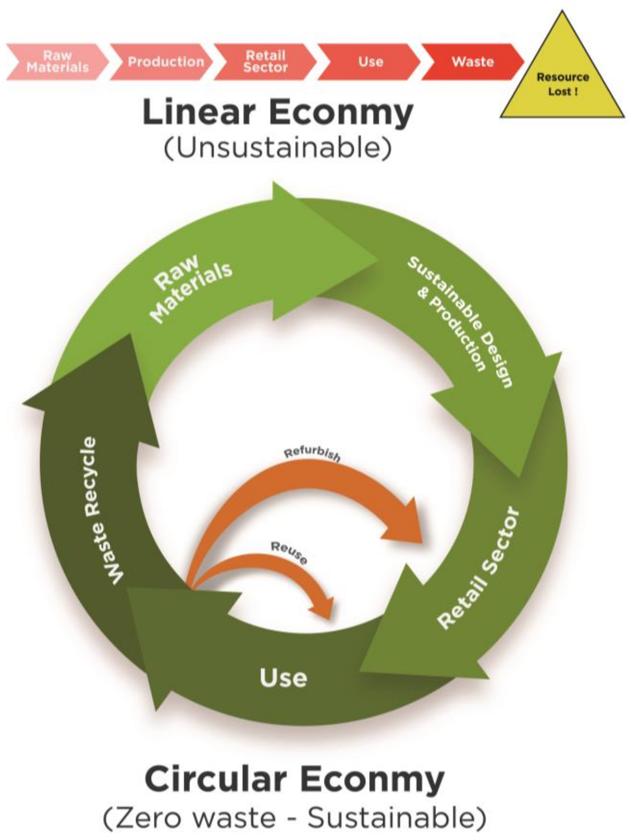


Figure 1. Circular economy (CE) model in contrast with the present linear economy model.

The sheer magnitude of biomass production in agricultural sector makes this sector a primary focus of CE model. It is projected that adopting principles of CE model in further development of Indian agricultural sector and food system could lead to benefits of USD 61 billion in 2050, cut greenhouse gases (GHG) emissions, and reduce environmental degradation (Ellen MacArthur Foundation, 2016). CE model promotes regenerative agriculture with emphasis on efficient resource management by prolonging the life of materials through incorporation of waste into production processes (Duque-Acevedo et al., 2020). CE model also focuses on reduction in use of non-renewable inputs. A few traditional practices which encompass the principles of CE model in agriculture sector are exemplified below,

(i) Fish-Rice farming system**:** Variants of this farming method are practiced in China, Japan, and north-eastern and southern states of India. In this system use of fertilizers and pesticides is avoided. In the improved Fish-Rice-Duck system after rice seeding ducks are introduced in paddy fields to protect the young rice plants from insect-attacks. This is followed by the introduction of fish and paddy weeds. The paddy weed fixes nitrogen for the rice plants and acts as a source of food for fish and ducks. Further the droppings of fish and ducks provide nutrients to the rice plants.

(ii) Livestock-integrated agricultural practices: This is one of the oldest agricultural practice in tropical and developing countries (Patel et al., 2020). The animal excreta provides the necessary nutrients for the crops, reducing the dependency on chemical fertilizers. The agricultural residue is also used up as animal fodder. The decrease in use of chemical fertilizers helps in reducing GHG emissions. Gurukul in Kurukshetra, India has long been using this model to promote zero-budget natural farming where cattle urine and solid excreta, mixed in particular proportion, is used in place of synthetic fertilizers.

(iii) Push-pull method: This method is used to protect cash crops from particular pests. It is close to intercropping strategy. However in this method a cash crop is planted with plants that repel/push-away particular pests by secreting kairomones (Agelopoulos et al., 1999; Patel et al., 2020). On the perimeter of the field the plants that attract the same pests are planted so that pests prefer to eat these plants in place of the main cash crop. For example, maize can be intercropped with *Desmodium uncinatum* (push species) and *Pennisetum purpureum* (pull species) on field's perimeter for protection against stemborer moth (Khan et al., 2010). The push-pull strategy helps in reducing the use of pesticides.

The other approaches like agroforestry based agricultural practices which include intercropping, and crop-rotation are also sound practices. The adoption of CE model in agriculture requires careful planning with biotechnological, biochemical, and ecological scientific knowledge as main input factors. CE in minimizing waste promotes the use of secondary raw materials which can be categorized as value-added secondary products. Next section discusses various approaches via which agricultural waste is being turned into variety of value-added products.

3. Value-Added Products from Agriculture Waste

3.1. Biofuels

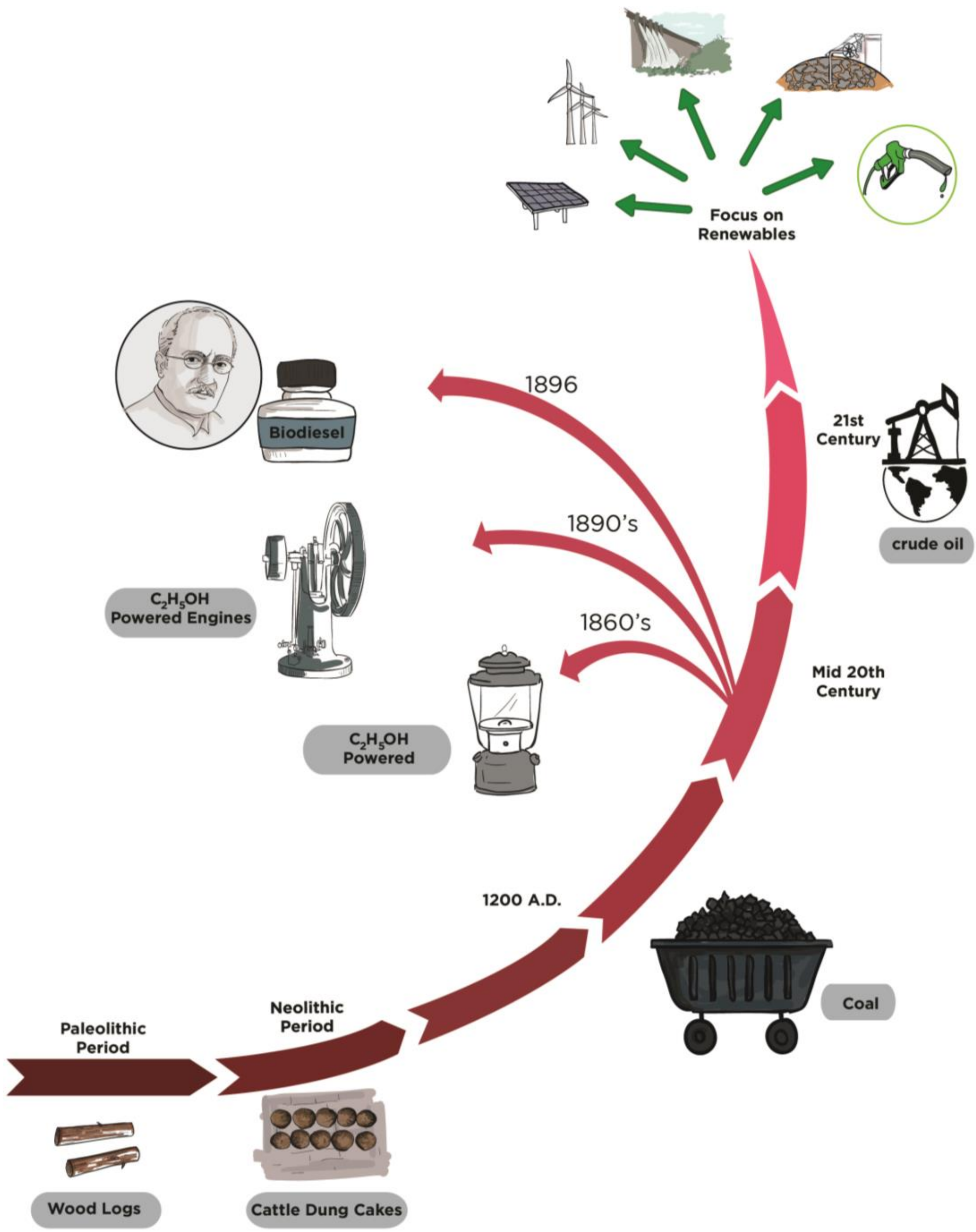


Figure 2. An outline of biomass use as a source of energy in different times.

The current economy is mainly driven by energy derived from fossil fuels. Fossil fuels were formed by anaerobic decomposition of buried organic matter (biomass: plants and animals) over a span of millions of years. The combustion of fossil fuels releases this CO_2, stored for millions of years, into the atmosphere thereby increasing the amount of greenhouse gases in present times. A greener alternative to fossil fuels are biofuels which are also derived from biomass (mostly plants). However, biofuels are regarded as carbon neutral fuels because CO_2 released upon combustion of biofuels is nearly equivalent to CO_2 absorbed by plants during growth and this happens in a span of a year or so. The shorter time span required makes biofuels a renewable source of energy while fossil fuels are not. The use of biomass for energy is not new for humankind. However with time and reforming technology the form in which biomass is utilized for energy production is becoming more efficient and less polluting. Figure 2 depicts a brief timeline of biomass as a source of energy.

Humans have been using biomass as a source of energy since the discovery of fire. In Paleolithic period wood was the main source of energy. With the beginning of agriculture and domestication of animals in Neolithic period dung was also used for energy (Gur-Arieh et al., 2019). By 1200 AD the use of coal for energy, although less prevalent, was also reported.

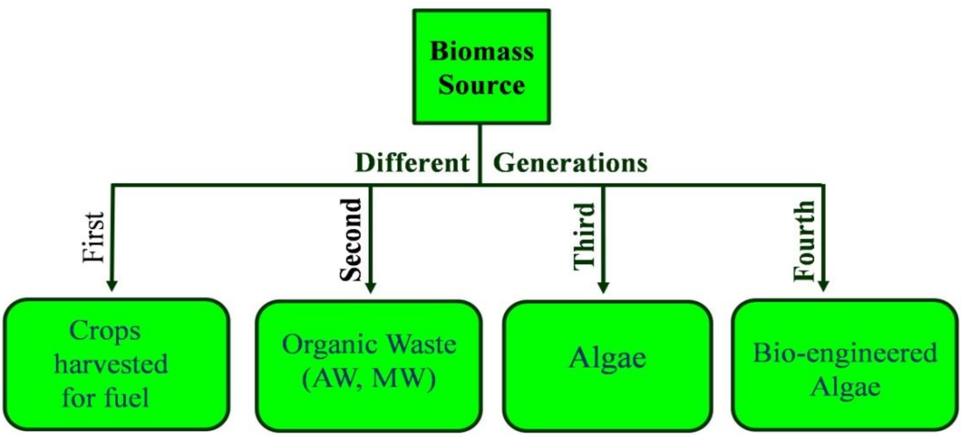


Figure 3. Sources of different generations of biofuels.
AW- Agriculture waste, **MW**-Municipal waste.

It is believed that Chinese used coal as a source of energy as early as 1500 BC (Cleveland, 2009). Between late 18thcentury to middle 20th century coal was the main source of energy. Although the crude-oil was used as fuel in China by 400 BC but its extensive use world-wide began in 20th century (Cleveland, 2009). The interest in renewable resources renewed largely after oil crisis of 1973 and 1979. The major biofuel industries were set up in USA and Brazil following oil crisis of 1970s (Cleveland, 2009). The earliest known biofuels are bioethanol and biodiesel. In fact, use of ethanol as a fuel goes back to 17th century when it was used for lamp-oil and cooking. In 1826 an American inventor Samuel Morey used ethanol to power the first prototype of American internal combustion engine. By 1860s ethanol was extensively used for lighting purposes. In 1876 German inventor Nikolas Otto invented 4-stroke internal combustion engine (ICE) which ran on ethanol. By 1890s ethanol powered engines were used in automobiles and farm machinery in Europe. The heavy taxation on ethanol in America compared to gasoline resulted in development of American

ICE adapted to gasoline (Bernton et al., 2010). Bioethanol has low calorific value than gasoline but it is a cleaner fuel because of higher oxygen content and octane number. In 1896 Rudolph Diesel invented Diesel engine along with the fuel Biodiesel which was derived from the transesterification of vegetable oil.

With an increase in environment consciousness stricter environment protection laws have been implemented. Hence once again greener options are being investigated and, biofuels are one such option. The major hurdle in use of biofuels is the debate between land-use for food vs. fuel. It is feared that switching to biofuels can put strain on land and water resources, eventually affecting the basic human needs for survival. However, the use of agricultural waste as a raw material for biofuel production offers a viable path without any compromise on food security. Biofuels look promising with recent advances in the field. Biofuels can be obtained from agricultural waste through biochemical, thermochemical, and chemical routes. At present we can categorize biofuels into four main generations depending on the source of biomass (Figure 3). Biofuels derived from agricultural waste are second generation biofuels. Irrespective of the source, biofuels obtained through biochemical conversion technologies are mainly derived through the fermentation of sugars present in organic matter.

3.1.1. Production of Bioethanol, Biobutanol, Biohydrogen and Biogas through Biochemical Conversion Routes

Agricultural waste comprising of crop-residue, agro-industrial waste and waste of fruits/vegetables can be subjected to fermentation. However due to greater amount of lignocellulosic material (80 - 85%) in agricultural waste the pretreatment for the release of sugars requires more energy. Consequently, the second-generation biofuels are costlier than first generation biofuels. The livestock waste subjected to anaerobic fermentation is a good source of biogas and is widely used in rural areas.

The biomass composition based upon proximate (moisture, fixed carbon, ash, volatile solids), ultimate (elemental analysis- CHONS), lignocellulosic composition (cellulose, hemicellulose and lignin), and biochemical analysis (carbohydrates, proteins and lipids) is used to assess the potential of a particular biomass source for fuel production (Pattanaik et al., 2019). A range of biofuels, like bioethanol, biobutanol, biohydrogen, and biogas, can be derived from biomass using different conversion technologies. Pattanaik et al. present a comprehensive review relating biomass composition to its fuel efficacy and suitability of particular biomass-to-fuel conversion method (Pattanaik et al., 2019).

The process of conversion of agricultural waste to biofuels starts with its pretreatment. Pretreatment is required to delignify the feedstock, as agriculture waste has high content of lignocellulosic matter like cellulose, hemicellulose, and lignin held up together forming highly complex matrix. Out of the three, lignin is most stable and is highly resistant to degradation and hydrolysis. Figure 4 shows structure of cellulose and three monomeric units of lignin. Hemicellulose acts as a binder between lignin and cellulose. It is an amorphous branched polymer of pentose (e.g., xylans, arabinose) and hexose sugars. Out of the three constituents of lignocellulosic matrix, hemicellulose component is the only one that can be easily hydrolyzed. Lignin is a three-dimensional amorphous polymer formed by polymerization of three phenylpropanoid alcohols known as monolignols. Monolignols are p-coumaryl alcohol, coniferyl alcohol and sinapyl alcohol. The percentage of these three monolignols in lignin differs from one plant species to another. Cellulose, the third component of lignocellulosic matrix, is the most abundant material on the earth. It is a crystalline linear polymer with cellobiose as a repeating block. Cellobiose is a disaccharide of glucose linked via β-1,4 glycosidic linkages. Because of its crystalline nature cellulose is hard to depolymerize. Therefore to make sugars present in lignocellulosic matrix accessible for hydrolysis and degradation several pretreatment methods – physical, chemical, biological, and physiochemical are employed. Physical processes like milling and irradiation decrease the crystallinity of cellulose and lead to depolymerization of lignocellulosic matrix (Pattanaik et al., 2019). The chemical methods are used for delignification of biomass. Now-a-days, green chemical methods like use of organic solvents, ozone, and ionic liquids are preferred over the traditional acid/alkali-based pretreatment procedures. The biological pretreatment employs a few fungi and bacteria species for the degradation of lignin. But biological delignification is a slow process. The physiochemical methods use combination of physical and chemical processes for hydrolysis and degradation. These methods include steam explosion, ammonia fiber explosion, CO_2 explosion, and wet oxidation (Chin and H’ng, 2013).

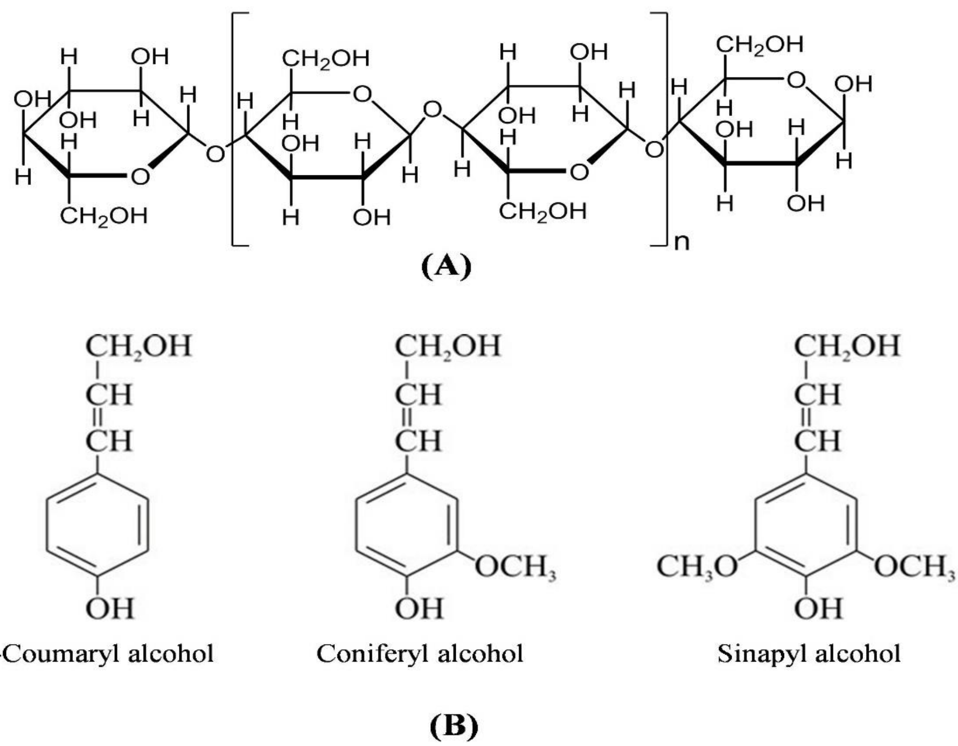


Figure 4. Panel (A) presents polymeric structure of cellulose showing β-1,4 glycosidic linkages. Panel (B) presents structures of three monomeric units of lignin.

After pretreatment, detoxification is carried out for the removal of by-products generated during the pretreatment processes. These by-products are known to inhibit the enzymatic action required for fermentation. Detoxification can be done through chemical treatment, liquid-liquid extraction, liquid-solid extraction, and microbial routes. The subsequent steps involve hydrolysis followed by fermentation. Hemicellulose and cellulose in pretreated biomass are broken down into monomeric units during hydrolysis using either acids or enzymes. Acidic hydrolysis is not eco-friendly and also corrodes the equipment while enzymatic hydrolysis is environment friendly. The different classes of enzymes used for hydrolysis are cellulases (convert cellulose into glucose), hemicellulases (liberate pentose and hexose sugars) and lignanses (enhance accessibility and facilitate action of cellulases and hemicellulases). The process of hydrolysis is also known as saccharification. The final step in biomass to biofuel conversion is microbial fermentation.

3.1.1.1. Bioethanol

Traditionally the microbial host for bioethanol production from corn-starch/sugarcane juice (edible sources) is *Saccharomyces cerevisiae* (yeast) which has also been genetically engineered to improve the ethanol yield. *S. cerevisiae* converts hexose sugar i.e., glucose to pyruvate via glycolysis process. Under anaerobic conditions, pyruvate with the subsequent enzymatic action of pyruvate decarboxylase and alcohol dehydrogenase is converted to ethanol. But similar efficient microbial fermentation of feedstock based on lignocellulosic matter is challenging as traditionally used *S. cerevisiae* and *Escherichia coli* do not ferment pentose sugars. Moreover the remnants of inhibitor compounds (e.g., phenols, furfural) affect fermentation efficiency. Several strategies have been developed to improve the ethanol production efficiency from lignocellulosic feedstock. The strategies are listed below and have their own merits/demerits (Alia et al., 2019; Pattanaik et al., 2019).

(i) Separate hydrolysis and fermentation (SHF)
(ii) Simultaneous saccharification and fermentation (SSF)
(iii) Simultaneous saccharification and co-fermentation (SSCF)
(iv) Consolidated bioprocessing (CBP)

The microbes preferred for the fermentation of lignocellulosic matter are those which can simultaneously ferment both hexose as well as pentose sugars. Some of these are: *Pichia stipitis, Candida shehatae, Pachysolentannophilus* (Yeasts), *Clostridium thermohydro-sulfuricum, Butyrivibriofibrisolvens,* genetically modified *E. coli* and *Zymommonasmobilis* (Bacteria) (Alia et al., 2019; Kim et al., 2010; Pattanaik et al., 2019).

Although bioethanol has several advantages over gasoline but it has low-calorific value. It is only 70% of calorific value of gasoline. The gasoline-ethanol mixture in ratio 80:20 is the highest amount of ethanol that can be used as fuel, without any engine modification.

3.1.1.2. Biobutanol

Another biomass derived bio-alcohol is butanol which has better fuel properties than that of ethanol. It can be used in pure state as fuel without any engine modification unlike ethanol. The procedure of biochemical conversion has the same steps as involved in production of bioethanol, however the microbes used in conversion technology are different. The conversion of sugars to butanol is known as ABE (Acetone-Butanol-Ethanol) fermentation with products acetone, butanol, and ethanol produced in the ratio 3:6:1 (Pattanaik et al., 2019). Butanol production from biomass requires strict anaerobic conditions for fermentation and is carried out by *Clostridium* species (Bacteria). *Clostridium* species can ferment both hexose and pentose sugars. The recent progresses made in bioengineering the microbes and developing better strategies for bioethanol and biobutanol production are reviewed in references Geddes et al., 2011, and Lütke-Eversloh and Bahl, 2011, respectively. In addition, iso-butanol can also be used as a biofuel.

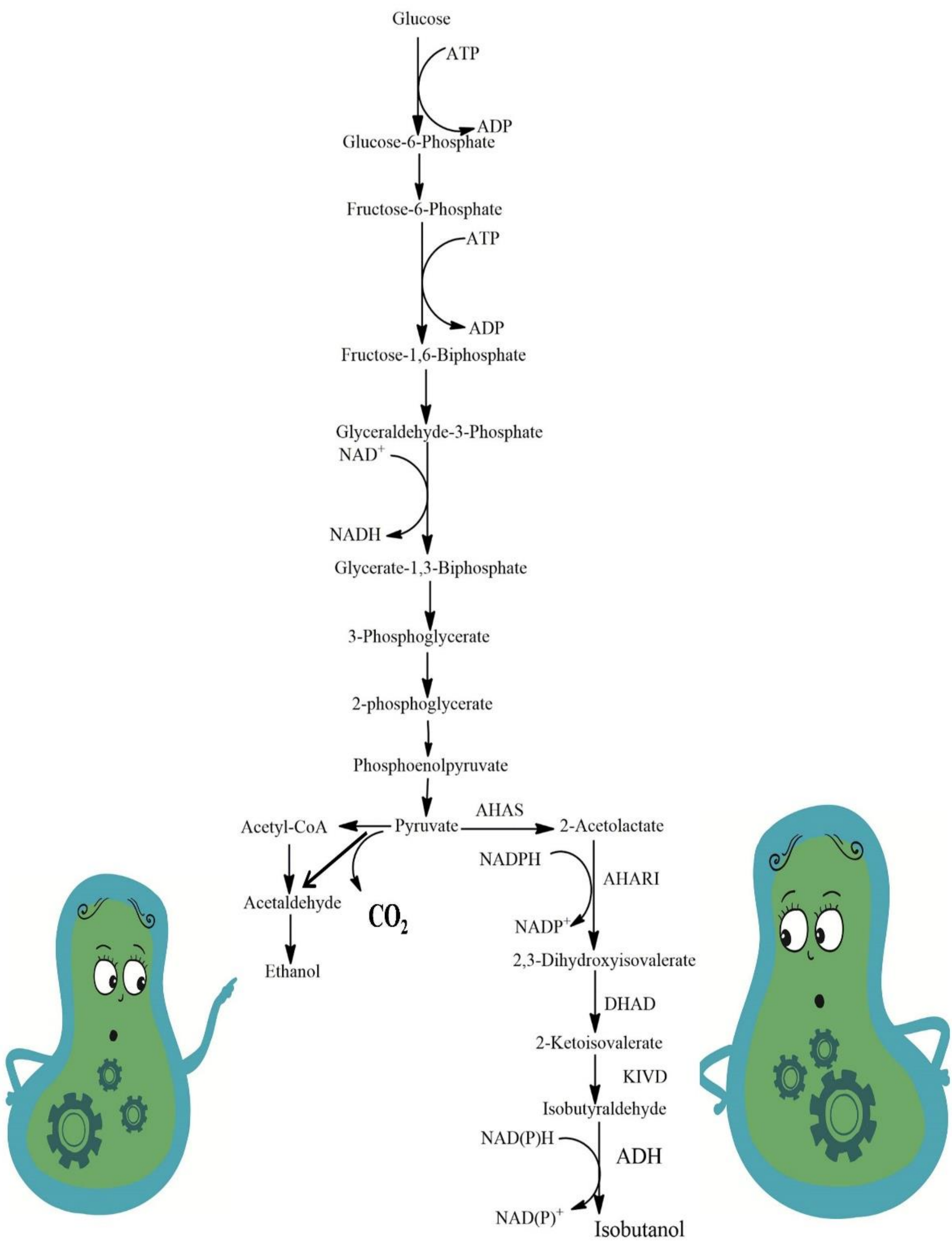


Figure 5. A schematic illustration of various biochemical steps involved in fermentation of sugars to ethanol and iso-butanol. For more details refer to Su et al., 2020.

A schematic illustration of biochemical steps involved in fermentation process leading to production of ethanol, iso-butanol, and butanol are presented in Figure 5 and 6, respectively based on reports by Su et al., 2020 and Qi et al., 2018. The various types of agricultural waste used for production of alcohol-based fuel include rice straw, wheat straw, corn stover, corn husk, barley straw, sugarcane bagasse, agro-industrial waste like oil palm fruit bunch, and fruit-waste like pineapple peel, banana peel, apple pomace (Pattanaik et al., 2019). Apart from fermentative alcohol (ethanol, butanol, iso-butanol) pathways, technologies have been developed to produce biofuels via non-fermentative 2-keto acid pathways resulting in production of linear and branched butanols (Kang and Lee, 2015). There are also fatty acid derived biofuels which are suitable alternative to diesel. Similarly isoprenoid derived fuels are alternative to diesel and jet-fuel (Kang and Lee, 2015). The other two types of fuels that can be produced from agricultural waste via biochemical routes are biogas and biohydrogen.

3.1.1.3. Biogas

Biogas production and utilization is perhaps more widespread in rural areas generally to meet the household cooking gas needs. The composition of biogas varies depending upon the properties of feedstock. It can be 50-75% CH_4, 25-50% CO_2, 5-10% water vapours, 0-1% H_2, 0-10% N_2, and 0-3% H_2S (Korbag et al., 2021). The other impurities that might be present in biogas are NH_3, volatile organic compounds (VOCs), CO, and siloxanes. Feedstock for biogas production can be lignocellulosic waste from crop-residues, live-stock waste, sewage sludge, and fruit-vegetable waste (FVW). The pretreatment for crop-residues is required. The biogas yield also depends on the composition of feedstock e.g., lipid-rich feedstock theoretically have higher methane production potential compared to carbohydrate and protein rich feedstock (Pattanaik et al., 2019). The high protein content of feedstock produces NH_3 leading to increase in pH of digestor and thereby inhibiting the microbial activity. The ideal carbon to nitrogen ratio of feedstock should lie in range between 20:1 and 30:1. Live-stock manure is appropriate feedstock for biogas production with C/N ratio of (29: 0.82), high organic and moisture content. It has been found that instead of using single substrate (e.g., only livestock manure), the use of two or more substrates enhances the biogas yields (e.g., livestock manure mixed with carbohydrate-rich substrate) (Korbag et al., 2021).

Biogas is produced through anaerobic digestion of organic matter and consists of four stages: hydrolysis, acidogenesis (fatty acids are generated), acetogenesis (acetic acid, CO_2, H_2 are produced), and methanogenesis (methane production stage). The various methanogenesis pathways discussed by Korbag et al., 2021 are:

$4CH_3COOH \rightarrow 4CO_2 + 4CH_4$ (Acetotrophic Pathway)

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ (Hydrogenotropic Pathway)

$4CH_3OH + 6H_2 \rightarrow 3CH_4 + 2H_2O$ (Methylotrophic Pathway)

The anaerobic digestion may be single-stage operation which although less efficient but is simple to use. The other mode of operation is two-stage and is more efficient. In two-stage digestors hydrolysis and acidogenesis are carried out in the first stage while in second stage acetogenesis and methanogenesis are performed. The efficiency of biogas production of two-stage digestor is enhanced as conditions for growth of different microbes can separately be optimized.

Biogas has a lower calorific value due to the presence of impurities. Increasing the percentage of methane improves its calorific value. Biogas with 90% or more CH_4 can successfully be used as a transportation fuel in place of natural gas. To remove the impurities from biogas, it can be subjected to cleaning and upgradation processes.

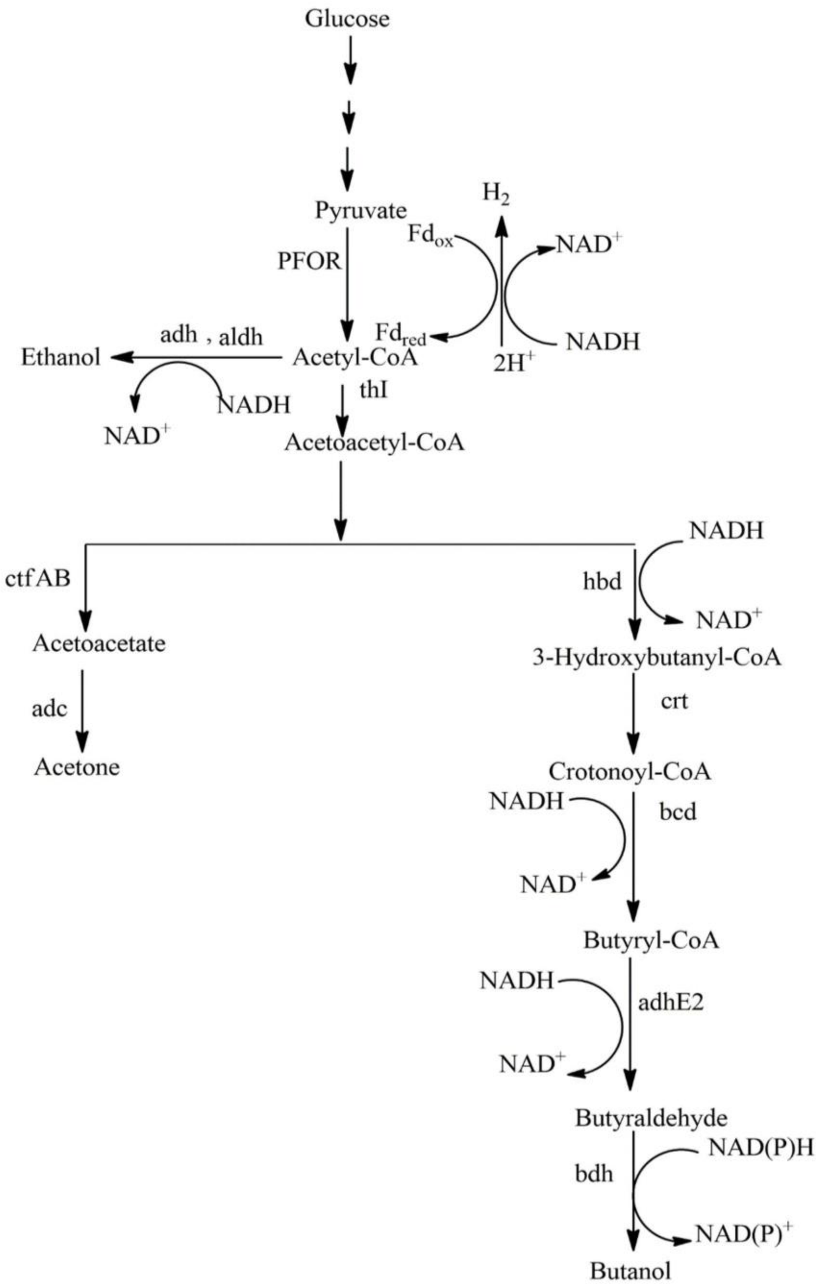
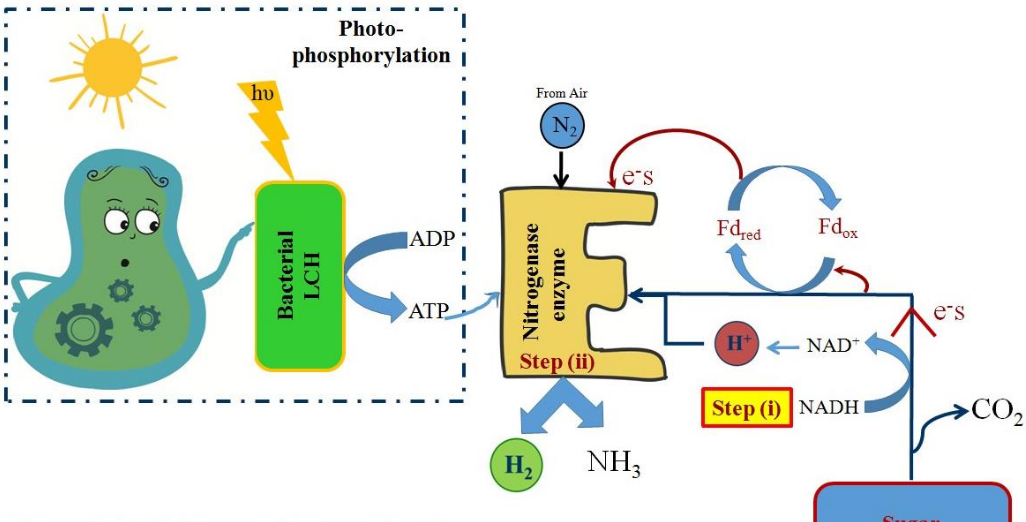


Figure 6. A schematic illustration of various biochemical steps involved in fermentation of sugars to butanol by *Clostridium species* (ABE fermentation). For more details refer to Qi et al., 2018.

3.1.1.4. Biohydrogen

Biohydrogen production from agriculture waste is also a promising conversion route. Hydrogen is a clean fuel and when synthesized via sustainable route is called biohydrogen. Biohydrogen can be generated via light-dependent and light-independent processes. The light dependent processes include direct bio-photolysis, indirect bio-photolysis, and photo-fermentation. The light independent processes are dark fermentation and microbial electrolysis. Agricultural waste can be used as a feedstock for photo-fermentation, dark fermentation, and in microbial electrolysis. All these three conversion routes are briefly described here. Photo-fermentation involves fermentation of hexose sugars derived from pretreated, hydrolyzed lignocellulosic matter by nitrogenase enzyme present in photosynthetic bacteria or anaerobic bacteria strains (Rhodobium, Rhodobacter, Rhodospirillum, and Rhodopseudomonas) (Hitam and Jalil, 2020). It is an energy intensive process because of high activation energy barrier involved in the process (Figure 7). The sugars are metabolized in bacteria to produce CO_2 and NADH. NADH transfers electrons to reduce ferredoxins. The reduced ferredoxins through certain complexes transfer these electrons to nitrogenase enzyme. The complexes use proton gradient to drive this electron transfer process. Finally at the active site of nitrogenase, hydrogen, and ammonia molecules are generated with the hydrolysis of ATP. ATP required for this step is generated via photo-phosphorylation. Figure 7 provides schematic representation of the discussed photo-fermentation process.



$$\text{Step (i): } NADH \rightarrow NAD^+ + H^+ + 2e^-$$

$$\text{Step (ii): } N_2 + 8H^+ + 8e^- + 16ATP \rightarrow 2NH_3 + H_2 + 16ADP + 16P_i$$

Figure 7. Biochemical steps involved in photofermentation of agriculture waste to biohydrogen.

Dark fermentation does not require any photon and proceeds via glycolysis of sugars to pyruvate. Under anaerobic conditions, pyruvate can take up two pathways depending upon whether facultative or obligate anaerobes are used for fermentation. Facultative anaerobes are tolerant to oxygen while obligate anaerobes cannot survive in presence of oxygen. The facultative anaerobes convert pyruvate to acetyl-CoA and formate in presence of enzyme pyruvate formate lyase (PFL). The formate is then converted to CO_2 and H_2 by the catalytic activity of formate hydrogen lyase (FHL) (Figure 8). Obligate anaerobes oxidize pyruvate to acetyl-CoA and CO_2 mediated by pyruvate ferredoxin oxidoreductase (PFOR). PFOR transfer electron to reduce ferredoxin (Fd). Fd further supplies these electrons to hydrogenase where H^+ supplied by redox mediator NADH (facilitated by NADH-dehydrogenase) is reduced to H_2 (Figure 9).

The third conversion route employs advanced anaerobic digestion reactor called microbial electrolysis cell (MEC). In MEC anaerobic bacteria are grown on anode. These bacteria are known as anode respiring bacteria (ARB) and consume (oxidize) organic matter converting it to CO_2 and supply electrons to the solid surface of electrode. The e^-s (electrons) through external circuit reach cathode where H^+ are reduced to produce desired H_2 gas. This process is referred to as electrohydrogenesis. A small electrical potential is needed to drive microbial degradation. The potential advantage of MEC over dark fermentation is high H_2 recovery. H_2 recovery from MEC is more than 90% compared to 33% from dark fermentation (Logan et al., 2008). However further research in direction of optimizing parameters for commercial viability of MEC is required. The influence of parameters like electrode materials, cell design etc. on MEC performance are discussed in a recent review by Yasri et al., 2019. More details regarding biohydrogen production can be found in Mohan and Pandey, 2013. A basic design of MEC is shown in Figure 10.

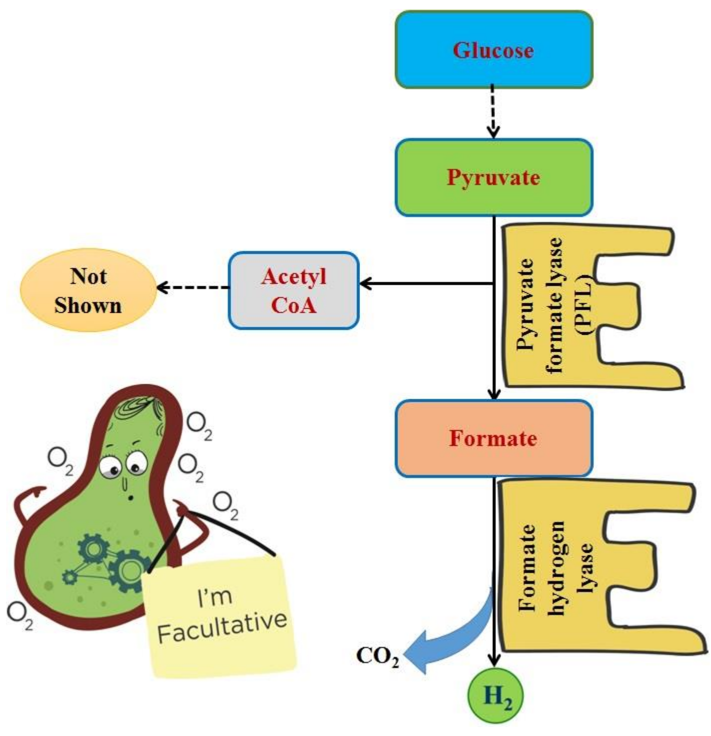


Figure 8. Biochemical steps involved in dark-fermentation of agriculture waste to biohydrogen by facultative anaerobes. Note that steps related to further metabolism of Acetyl-CoA are not shown.

Biohydrogen production can use wastewater from agro-industries and pretreated agricultural waste as a feedstock. Different agricultural wastes that have been used for H_2 production include sugarcane bagasse, corn stover, rice straw and bran, wheat straw, and apple pomace (Pattanaik et al., 2019). Likewise wastewater from agro-industrial sector is rich in carbohydrates (e.g., potato processing wastewater, cheese whey etc.) and holds potential for biohydrogen production. The integration of wastewater treatment with biohydrogen production is profitable and promotes CE practices. Biohydrogen production from nitrogen-rich livestock waste is less efficient due to inhibitory action of generated ammonia at high concentrations (Pattanaik et al., 2019). The livestock waste can be used as feedstock with improved yield but feedstock has to be meticulously selected. For example, Wu et al. report improvement in hydrogen production following co-digestion of manure with carbohydrate-rich substrate (Wu et al., 2009).

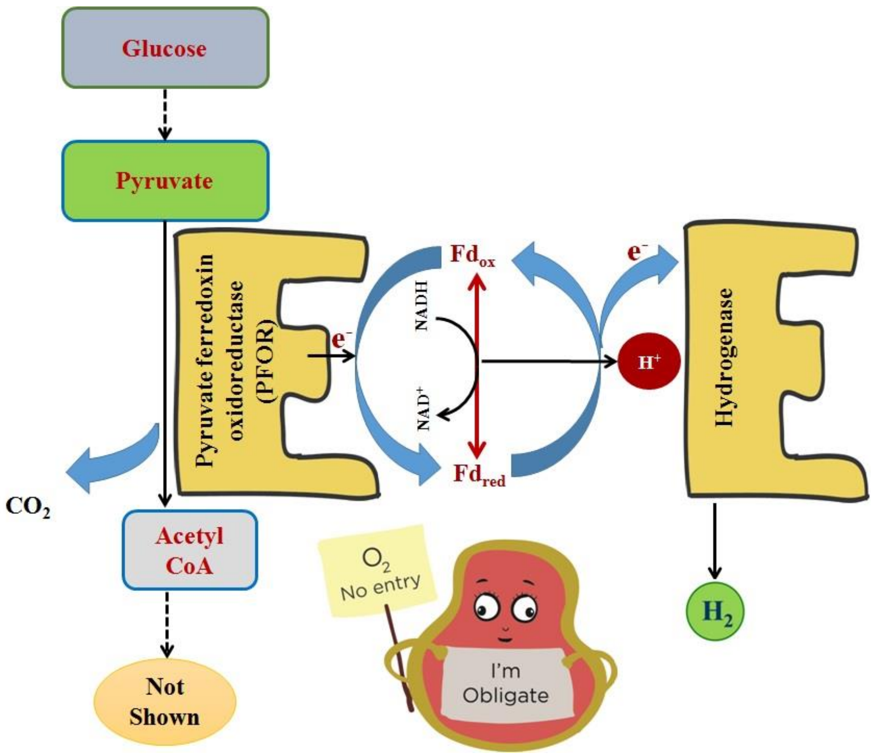


Figure 9. Biochemical steps involved in dark-fermentation of agriculture waste to biohydrogen by obligate anaerobes. Note that steps related to further metabolism of Acetyl-CoA are not shown.

3.1.2. Production of Biodiesel Through Chemical Conversion Route

Fatty acid derived biofuels are popularly categorized as Biodiesel. Biodiesel is obtained from organic oil derived from plants. The plant oil are triesters of glycerol and long-chain fatty acids. These triesters are commonly called triglycerides. Once oil is extracted from plant source, the process of biodiesel production involves transesterification of triglycerides where upon by reaction with alcohol (either methanol or ethanol) in presence of base (NaOH, KOH) or acid (mineral acids) catalysts one ester is replaced by another (Figure 7). The use of enzymes is also reported for enhancing the conversion efficiency (Kang and Lee, 2015). The by-product of transesterification process is glycerol. The quality of plant oil in terms of free fatty acid (FFA) content is important to assess before the same can be subjected to transesterification. FFA content increases under conditions that break away the fatty acid chain from glycerol molecule, for example, under conditions where high water content is present in oil or oil is subjected to high temperatures. Plant oil to biodiesel conversion is a single step reaction for oils with lesser FFA content. But for oils richer in FFA, an additional pretreatment step is required or else the formation of soap takes place during transesterification reaction in presence of base catalyst which reduces the biodiesel production yield. This additional step is esterification of FFA where fatty acids are converted into esters and subsequently the transesterification is carried out (Figure 11). Agricultural waste is also a rich source of plant oil particularly agro-industrial waste. The examples include rice bran (oil content 16.8%), waste cooking oil (from household/restaurants/food industry), spent coffee ground (residue of brewed coffee; oil content 10-15%), deoiled cakes of edible oil (e.g., palm oil, canola oil, olive oil etc.), and non-edible oil seeds of jatropha, neem, cottonseed etc. which can be used as raw material for biodiesel production (Pattanaik et al., 2019).

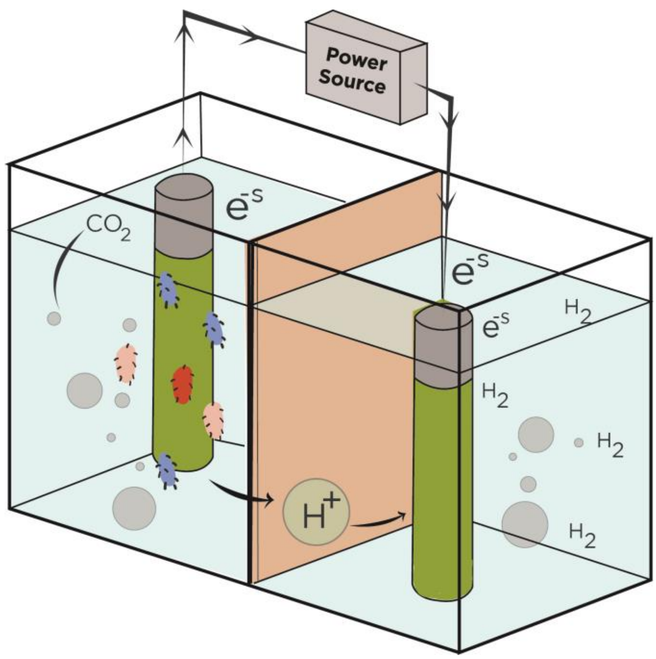


Figure 10. Basic design of Microbial Electrolysis Cell (MEC).

3.1.3. Production of Biofuels Through Thermochemical Conversion Routes

The different thermochemical routes available for biofuel production are pyrolysis, gasification, and torrefaction. The other technology under development is direct liquification. The thermochemical routes can use any type of biomass as feedstock. For thermochemical routes conversion time is significantly lesser and end products are cheaper but it requires high operational temperatures in comparison to biochemical routes. Through these routes biomass, depending on its properties, can be converted to solid, liquid, or gaseous fuel. The main products of thermochemical processes are bio-oil, biochar, syngas, and bio-coal. Biomass needs to be pretreated via mechanical techniques to reduce the particle size, moisture content, and densification might also be required for low-density biomass (Ibarra-Gonzalez and Ben-Guang, 2019). The particle size is important parameter which controls the heating rate of feedstock impacting the output yield. Since no chemical pretreatment is required and technologies used are well-developed, the end product is cheaper in comparison to that derived from biochemical routes. However biochemical conversion provides greener routes to biofuels. Figure 12 presents an overview of thermochemical routes of biomass conversion. A brief discussion on these routes is presented below.

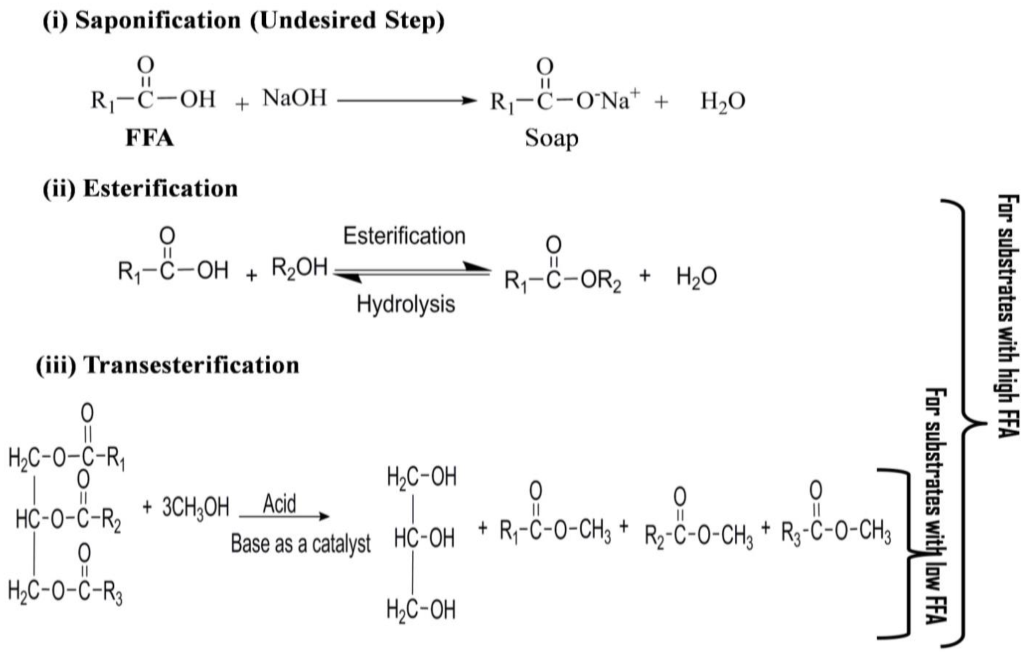


Figure 11. Chemical reactions involved in Biodiesel synthesis for substrates with low and high FFA (free fatty acid) content.

3.1.3.1. Pyrolysis

It is a process of thermo-chemical degradation of pretreated biomass carried out in the absence of oxygen. The temperatures required are in the range 450-500° C at atmospheric pressure. The residence time of feedstock in the reactor is in seconds. The products obtained are solid and volatile gases (flue gas). These volatile gases are subjected to rapid cooling to avoid cracking (break-down into smaller fragments) or polymerization (react to form bigger fragments). Upon condensation end-products are bio-oil, non-condensable gases, and biochar. The main desired product of pyrolysis is bio-oil. Bio-oil is used as a liquid fuel (no engine modification required). But since it is a mixture of number of oxygenated molecules including lignin derivatives with water content between 15-35 wt %, it is a low-grade liquid fuel. To improve the fuel properties of bio-oil it is subjected to refining procedures similar to crude-oil.

3.1.3.2. Gasification

In this process biomass is subjected to high-temperatures in range of 600-1000°C at atmospheric pressure in the presence of controlled amount of oxygen. The amount of oxygen fed into reactor is less than required for complete combustion of biomass. The residence time is in seconds.

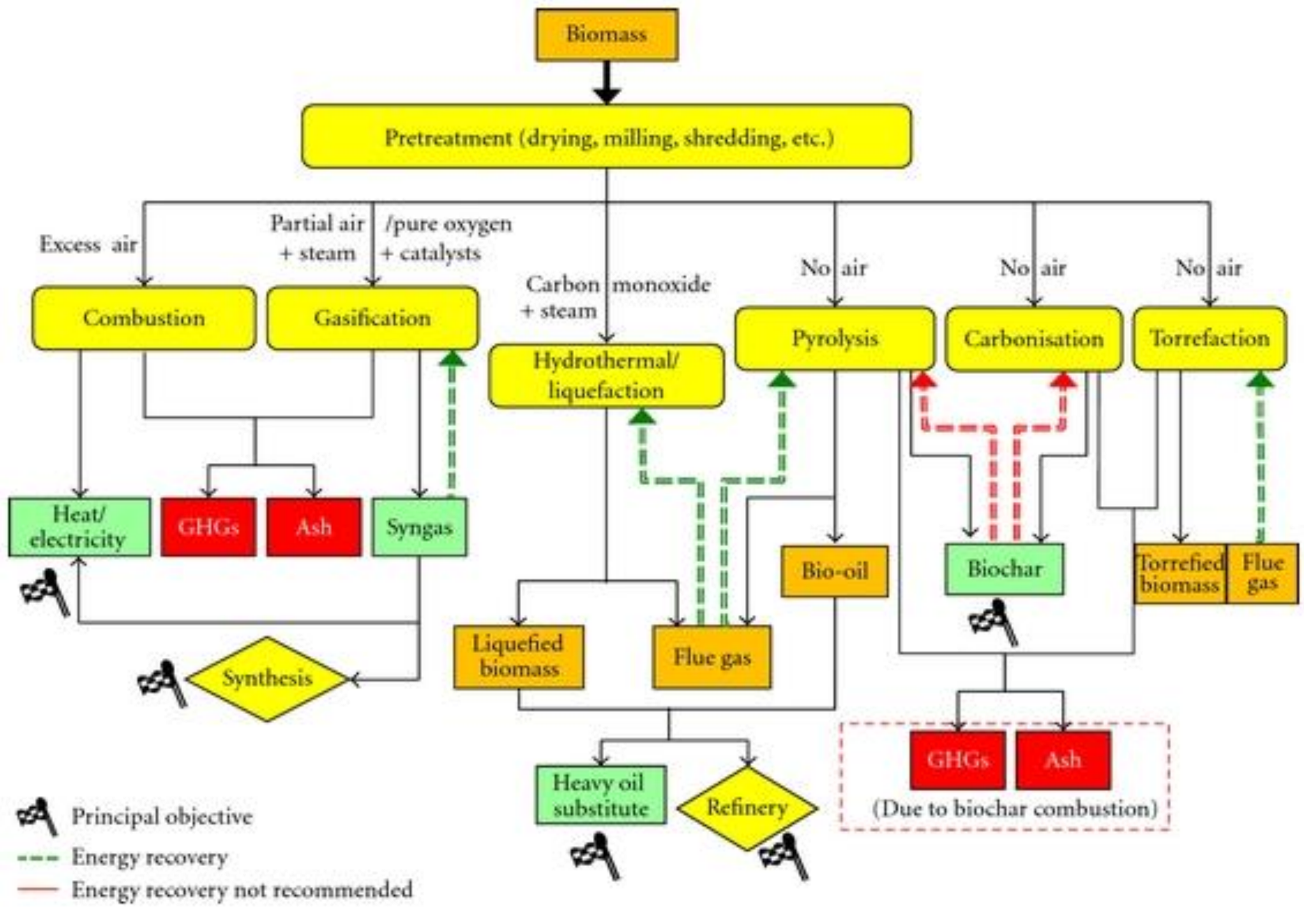


Figure 12. Flowchart of different thermochemical routes for biomass conversion. Source: Verma et al, 2012 [Copyright © 2012 M. Verma et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.]

The main objective is to convert biomass to gaseous products. The composition of gas depends on the type of biomass. The obtained gases are purified of impurities like H_2S, COS, N_2, and nitrogen compounds. The end-product is syn-gas, mixture of CO and H_2. Syngas is a valuable starting material for the production of liquid fuel via Fischer-Tropsch (FT) synthesis or hydrogen via Water Gas Shift reaction (WGSR). Syngas is also used as a raw-material in the production of fine-chemicals.

3.1.3.3. Torrefaction

It is a process in which biomass is heated in the absence of oxygen at relatively lower temperatures in range of 200-315°C releasing the moisture present in biomass along with volatile compounds. The end-product is relatively dry, brittle solid mass with properties similar to coal and is referred to as bio-coal (torrefied biomass). Another process similar to torrefaction is carbonization which converts biomass to biochar. Biochar can be used as a fuel as well as additive for maintaining the quality of fertile soil. Biochar is also a good adsorbent.

The agricultural waste which is being used in thermochemical conversion technologies include wheat straw, oat straw, whole barley straw and hull, flax straw, corn cobs and stover, olive oil residue, palm oil residue, and livestock manure. The end-products obtained from these have calorific value in range 15-35 MJ/kg (Verma et al., 2012).

3.2. Soil Management

The use of industrial (non-organic) fertilizers to maintain the fertility of soil is becoming a matter of concern. The excessive use of fertilizers is proving to be detrimental to the health of soil, plants, and humans. Fertilizer overuse increases salinity and acidity of soil, kills beneficial micro-organisms, causes eutrophication of water-bodies, and leads to GHGs emission. For example, excess of N_2 added to soil is converted by microbes to N_2O which has global warming potential about 300 times that of CO_2. Also industrial fertilizers add large quantities of nutrients to soil in a relatively short time-span which disturbs the microbial ecosystem of the soil. Traditionally livestock-manure has been used to improve the fertility of soil but the presence of pathogens in raw manure can induce diseases in crops. Moreover the improvement in soil fertility is marginal leading to low crop yields. Historically this made organic fertilizers a lesser preferred choice over non-organic fertilizers. However, now-a-days diverse and better organic fertilizers are available. These include; organic compost, anaerobic digestate, and biochar. All these present a perfect example of closed resource loops in accord with the practices of circular economy. Agricultural waste can be converted to anaerobic digestate and biochar. The conversion of agricultural waste to these value-added products itself mitigates climate change as the release of GHGs (CH_4, CO_2) is prevented. The decomposition of waste in landfills is a significant source of GHGs.

Anaerobic digestate is solid-residue produced upon biogas synthesis while biochar is end product of thermochemical conversion routes. Digestate being a by-product of anaerobic digestion of organic matter (e.g., crop residues, livestock-manure) is an excellent source of all plant nutrients because during anaerobic digestion no loss of nutrients takes place (Lukehurst et al., 2010). Digestate slowly releases nutrients into the soil. Pathogens are also killed during pretreatment step. Therefore digestate is a greener and more soil-friendly option over non-organic fertilizers.

Biochar is a carbon-rich source. It is constituted of organic matter – carbon, hydrogen, oxygen, sulphur, nitrogen, and minerals like silica, aluminium, calcium, magnesium, phosphorus, sodium, and potassium. Therefore biochar is a good source of NPK nutrients (nitrogen, phosphorus, potassium) mainly required for plant growth. Biochar is a good adsorbent with large number of surface functional groups, high porosity, and surface area. It improves the soil quality by improving aeration, water holding capacity, and increasing cation exchange capacity sites facilitating nutrient retention (Jindo et al., Part1 2020; Jindo et al., Part2 2020). Biochar with carboxyl and phenolic carbon groups has a higher cation exchange potential allowing it to adsorb more nutrients. It retains nitrogen in the soil thereby preventing the release of N_2O. Biochar is alkaline in nature and is known to have positive impact on the fertility of acidic soils. However, it has no impact on alkaline soils. The influence of biochar on soil properties depends on the nature of feedstock, pyrolysis conditions, pH of soil, and crop to be cultivated. For example, biochar produced from livestock-manure and crop-residues have high phosphorous content in acidic soils (Jindo et al., Part1 2020). Similarly the biochar produced from rice-straw provides potassium to crops that can easily be adsorbed.

Being a good adsorbent biochar can stabilize (i.e., adsorb) contaminants in soil reducing the harmful effect of these contaminants on the plant-growth as well as preventing heavy metal contaminants entry into food-chain. Biochar promotes microbial growth and as a result it is added to compost to enhance its agroeconomic value. For example, a mixture of compost with addition of small amount of biochar increases the nitrogen content of compost as well as speeds-up the process of composting. The biochar added to anaerobic digestor improves the nutrient value of digestate and also promotes anaerobic digestion by microbes (Hu et al., 2021). However, at present biochar should only be used as an additive. It is because higher application rate of biochar can also negatively impact the plant growth. More research in this regard is required.

3.3. Bioplastics

The plastics have become an integral part of modern life. Today it is not possible to imagine a day-to-day routine free from the use of plastics. Plastics are derived from fossil fuels and hence are non-renewable in nature. In addition the production of plastics adds GHGs to environment and its biodegradation takes place over duration of 500-800 years. As a result, there are strong chances that these will end up in marine environments. It is known that plastics do not degrade in marine environment and become a potential choking hazard for marine life. Therefore, alternatives to plastics that biodegrade and do not lead to GHGs emissions are highly desired. Bioplastics derived from biomass are emerging as promising alternatives especially the second-generation bioplastics which are derived from agricultural waste. Second-generation bioplastics are based upon cellulose, starch, chitosan, polylactic acid (PLA), and polyhydroxyalkanoates (PHA). PLA and PHA have properties similar to their non-renewable fossil fuel derived counterparts (Figure 13). Hence, out of many classes of bioplastics, we shall here be focussing on PLA and PHA only. For more comprehensive reviews on other classes see Gonçalves de Moura et al., 2017 and Chan et al., 2021.

PLA is an aliphatic polyester derived via the fermentation of organic matter followed by polymerization. Fermentation converts dextrose to lactic acid. Lactic acid dimerizes to form lactides. These lactides in presence of a catalyst undergo ring-opening polymerization to yield high molecular weight PLA. The SSF (Simultaneous saccharification and fermentation) strategy gives the best yields. PLA has stereoisomers and depending on its stereochemical nature can either be isotactic or atactic. PLA is promising alternative to polyethylene terephthalate (PET), polystyrene (PS), and polycarbonate (PC). It finds applications in packaging, textiles, medical, electronics, and agriculture (Chan et al., 2021). To detail a few applications, PLA is used for bone and tissue engineering, wound treatments, and in medical implants like rods, plates, and screws. It has excellent fibre properties which include resistance to UV radiation. In agricultural sector, it is used as mulch film that facilitates the slow release of fertilizers into the soil (Chan et al., 2021). The sources of agricultural waste used for PLA synthesis are Cassava bagasse. It is converted to PLA using *Lactobacillus delbrueckii*, *Lactobacillus casei* with yield 0.90-0.98 g/g of substrate. Using Lactobacillus species PLA from wheat and rice bran is obtained with yield of 129 g/L. The other sources include sugarcane bagasse and empty fruit bunch from oil palm trees.

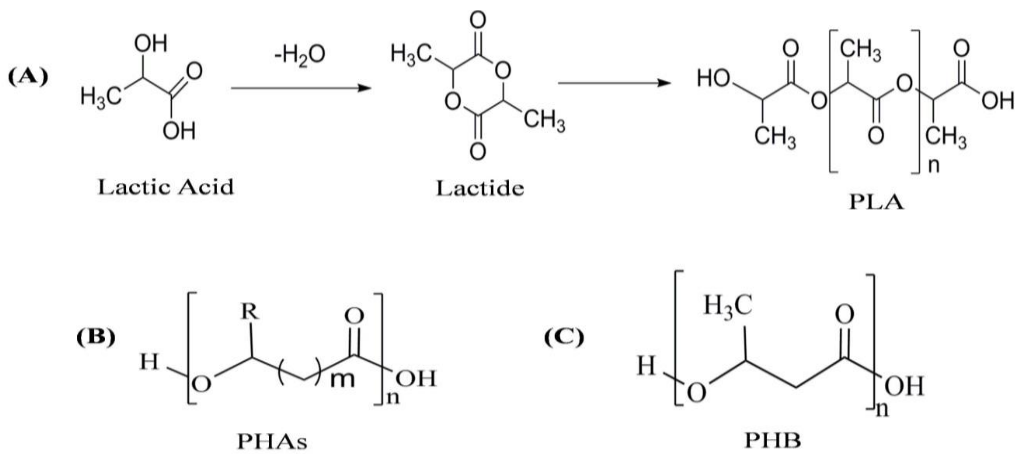


Figure 13. **Panel (A)** Polymerization reaction of lactic acid to polylactic acid (PLA). **Panel (B)** General structure of polyhydroxyalkanoates (PHAs), mostly with m=1. **Panel (C)** Structure of poly(3-hydroxybutyrate) (PHB).

PHA is also an aliphatic polyester with hydroxyl acid monomers polymerized in presence of microbes. The most prominent PHA is poly(3-hydroxybutyrate) abbreviated as PHB. It is a potential alternative to polyethylene (PE) and polypropylene (PP) (Adeleye et al., 2020). The agricultural waste sources from which PHAs can be derived include sugarbeet, sugarcane and soya molasses, wheat bran, whey hydrolysates, olive mill wastes, brewery wastewater, and palm oil mills effluents (Adeleye et al., 2020). It has applications in sector of biorefineries, medicine, packaging, agriculture, and construction industry (Adeleye et al., 2020).

PLA and PHAs despite their advantages have certain limitations. For example, PLA has good mechanical properties but it lacks desirable thermal properties. Also, it does not degrade in marine environment. Similarly PHA has poor mechanical properties. Therefore, additives like plasticizers and thermal stabilizers are required to be added to enhance these properties. The different blends of bioplastics can be synthesized to have a material with desired properties. Out of all, PLAs are cheapest bioplastics. In general the price of bioplastics is 2.5 to 7.5 times the prices of fossil fuel derived plastics (Packaging 360 website). However, cost economy of bioplastics has improved significantly in last few years. Earlier the prices of bioplastics were 35 to 100 times more than traditional plastics (Adeleye et al., 2020).

3.4. Construction Material - Reinforcement Additives

With rapid development taking place all around the world newer homes, offices, and building-complexes will continue to be constructed. The main component of concrete/mortar is cement. Cement industry is one of the largest industries in world. Cement acts as a binder between different construction materials. The production of cement contributes significantly to the GHGs emissions as cement formation is an energy intensive process. In 2015 cement industry generated about 2.8 billion tonnes of CO_2 which was 8% of total global contribution. To mitigate climate change sustainable alternatives to cement are being explored (He et al., 2020). For example, the use of biochar as an additive to mortar is found to increase mortar's strength by 15 to 20% (Hu et al., 2021). As previously discussed biochar is highly porous in nature. The porosity and pore-size of biochar is controlled by the nature of feedstock and conditions of pyrolysis. Biochar with micro-pores and meso-pores increase the strength of mortar while reverse is true for biochar with macro-pores. Therefore, careful analysis of physicochemical properties of biochar is required before it can be used as an additive for any purpose. Any additive to be used as structural construction material should provide required compressive strength. The biochar-additive added to replace cement in mortar should not exceed 10% by weight otherwise biochar starts to have negative impact on properties of concrete/mortar (Hu et al., 2021). Also heavy-metal contaminants should not be present in biochar. Biochar obtained from rice husk is known to provide resistant to cement from chlorine and sulphate attack (Muthukrishnan et al., 2019). The addition of finely crushed barely straw to concrete decreases its thermal conductivity by 5.71% (He et al., 2020; Belhadj et al., 2015). Palm kernel shell (PKS) is one of the most successful examples for the utilization of waste material in concrete pavement. In all these examples agriculture waste reinforces the strength of concrete. The reinforcing efficiency of agriculture waste is closely related to the nature of cellulose and its crystallinity which in turn is attributable to its cellulose fibril content that provides maximum tensile and flexural strength as well as rigidity (Foster 2015; Zakaria 2018).

The agricultural waste based value-added products are also finding utility as non-structural construction material (Adeleye et al., 2020). For example, the plastic foam used for providing thermal insulation in the building can be replaced by bioplastic based foams of PHA (Ivanov et al., 2015). Similarly a bioplastic based polymer composite of hemp and PHB can be used as an alternative to plywood (Christian, 2008). The mechanical properties of PLA are enhanced by addition of water bamboo husk (Wang et al., 2008). The composites prepared by combining nut shells with various petroleum-derived non-biodegradable polymers or biodegradable polymers like addition of walnut shell to urea-formaldehyde resin or to polyethylene, almond shell addition to polypropylene, groundnut shell addition to polyethylene etc., further improves the mechanical strength of these polymers. The advantage of bio-composites (natural fibre + biodegradable polymers) is that these can easily be disposed or composted without harming the environment (Foster, 2015).

3.5. Bioactive Compounds

An important application to which agricultural waste can be subjected is extraction of valuable bioactive compounds. These compounds are known as secondary metabolites and are present in all parts of the plants. They are synthesized by the plants for protection against parasites and oxidation. They also chemically attract pollinators to the plants. The chemical nature of secondary metabolites have numerous variations and these have been categorized into several classes: terpenoids, phenols, flavanoids, alkaloids, waxes, tannins, gums, carotenoids, and many others (Vuong, 2017).

For many centuries bark, plant stalks, leaves, roots were used to prepare medicines to treat different ailments. This specific class of compounds were alkaloids. The pharmacological properties of alkaloids like morphine, codeine, quinine, nicotine and cocaine are well known. These compounds are analgesic, central nervous depressants, antipyretic, antimalarial and have antitumor properties. Alkaloids like berberine and galanthamine are AChE inhibitors, antidiabetics, and antioxidants (Vuong, 2017). However in high concentrations alkaloids can be toxic to humans. Similarly phenol compounds have good antiproliferative, anti-inflammatory, anti-obesity properties and even provide protection against ultra-violet radiations (Jimenez-Lopez et al., 2020). To treat cattle infections, instead of antibiotics, tannins can be used. Tannins are also used in cosmetics. Caretnoids and tocopherols have excellent anti-oxidant properties and act as scavenging agents against reactive oxygen species. Flavonoids can reduce platelet aggregation and improve cardiac performance. Terpenes are responsible for flavours and fragrances, and also have antibiotic properties. Phenol compounds (PC) can be used as additives to increase the nutritional values of different foods (ice-creams and biscuits) and animal feed supplements. The use of such supplements led to better egg laying and egg colour in poultry farms (Zhang et al., 2019). The production and quality of milk also improved in case of cattle (Aguiar et al., 2014; Olagaray and Bradford, 2019). Due to their anti-oxidant and anti-microbial properties, PCs are used as food preservatives. Grape seeds extracts have high levels of polyphenols. This extract is applied to cookies and potato chips to inhibit the formation of toxic acrylamide in a variety of heat-treated commercial starchy foods (Xu et al., 2015; Zhu et al, 2011).

The recovery of these bioactive compounds from agriculture waste occurs in three steps; pretreatment, extraction, and purification. They are heat-sensitive therefore at no stage/step feedstock should reach high temperatures. Pretreatment varies and depends on the extraction method to be used. Pretreatment techniques can be foam mat, electro-osmotic de-watering, pulverization, and micro-filtration. These techniques remove microbes from the feedstock. Various extraction methods like maceration, salts, microwave assisted extraction, supercritical fluid extraction, pressurized liquid extraction, ohmic technologies, and multi-technique extraction approaches are available (Jimenez-Lopez et al., 2020). The extraction rate studies of citric acid from banana peel (an abundant source of waste, 190, 000 tons per year) by Kereem and Rahman, 2013 led to optimization of extraction conditions where 82 mg of bioactive compound per gram of dry weight waste (DW) is obtained. The extraction conditions were optimized by changing ethanol (EtOH) concentration, extraction time, and temperature. A similar condition optimization study with different solvents at different temperatures was carried by Dorta et al., 2014 for mango peels and seeds. For purification step either traditional methods like distillation or steam distillation are used or filtration membranes, resins or innovative chromatographic fragmentation methodologies can be employed. Adsorption is another good alternative available for the enhancement (Soto et al., 2011).

The residues of fruits, vegetables, coffee, tea, cereals or nuts are generally used for the extraction purposes (Mayanga-Torres et al., 2017; Munekata et al., 2016; Tsubaki et al., 2010; Babbar et al., 2011; Egüés et al., 2012). The field of plant derived bioactive compounds has been extensively researched. The composition of secondary metabolites in various agriculture waste substrates is well-documented along with their nutraceutical, pharmaceutical, and cosmetics applications.

3.6. Adsorbents

Adsorption is one of the simplest, efficient and cheapest methods of removing contaminants from soil, water, and air. Agricultural waste being lignocellulosic in origin is porous and contains many reactive groups (like carboxyl, hydroxyl, amides, amines, methoxy, thiols etc.) and still has good chemical stability. These groups promote adsorption of molecules and ions via various mechanisms; for example, chemisorption, physisorption, ion-exchange, chelation, electrostatic interactions, ligand exchange, particle diffusion etc. Sud et al., 2008 have discussed adsorption properties of agriculture waste towards heavy metal ions with a detailed overview of types of interactions operative between adsorbent and adsorbate. A recent review by Dai et al., 2018 presents a comprehensive overview of adsorption capacity of agricultural wastes towards chemically different types of adsorbates like heavy metal ions, dyes, drugs, pesticides, aromatic compounds, and oils. A few selective case studies are briefly summarized here. Rice husk is a good adsorbent for Pb(II) (Amer et al., 2017). Untreated walnut shell can effectively remove Cd(II) via ion-exchange interactions (Gondhalekar and Shukla, 2015). Song et al., 2015 found sulphur-functionalized rice husk and rice straw to be the good adsorbents for Hg(II) removal. Zhu et al., 2016 developed bismuth modified biochar derived from wheat straw for enhanced adsorption of As(III) and magnetic gelatine-modified biochar derived from chestnut as adsorbent for As(V) removal (Zhou et al., 2017). Biochar has excellent adsorption properties comparable to activated carbon.

The agriculture waste can also be modified for adsorption and removal of ions other than heavy metal ions. The high concentration of fluoride ion in drinking water especially in rural areas can cause fluorosis affecting teeth and bones. Long-term exposure can result in severe skeletal deformities including stiffness in joints. Paudyal et al. used multi-valent metal ions (Al(III), La(III), Ce(III), Ti(IV), Sn(IV), Zr(IV) and V(IV)) loaded dried orange juice residue (DOJR) gel as an adsorbent for removal of fluoride ions from water through ligand exchange reactions. Fluoride removal depends on type of loaded metal ions and pH. No interference in adsorption characteristics was observed in presence of ions like nitrates, chlorides but sulphates affected fluoride adsorption capacity of these gels (Paudyal et al., 2011; Paudyal et al., 2017).

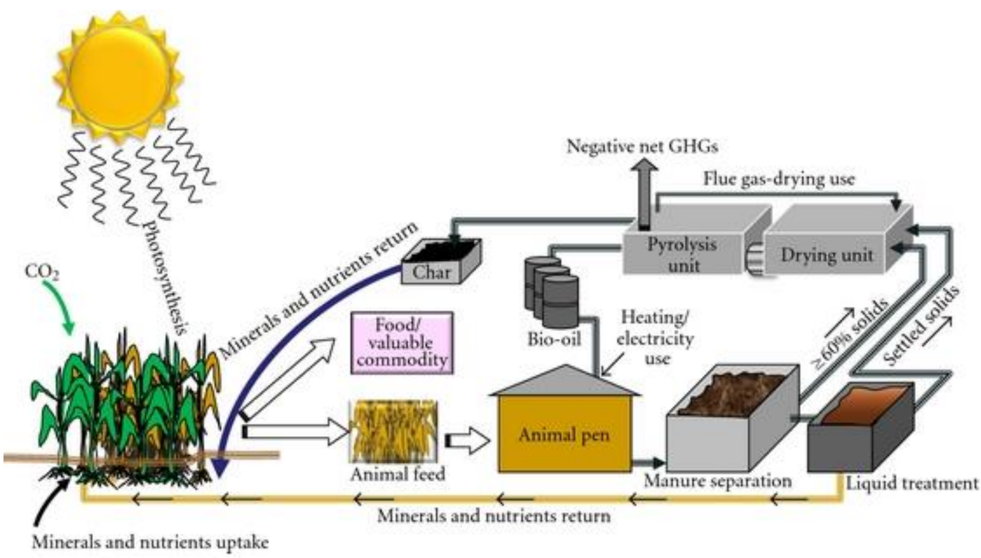
The organic contaminants can also be efficiently adsorbed by agriculture waste. For example, Ren et al., 2016 reported the removal of dyes from industrial wastewater using garlic waste. Banana peel based adsorbent is used for adsorption of polycyclic aromatic hydrocarbons (Gupta and Gupta, 2015). Barley straw, coconut shells, garlic, and onion skins based adsorbents are reported to facilitate oil removal (Ibrahim et al., 2010; Zhou et al., 2015).

3.7. Other Uses

Apart from numerous above listed applications there are a few more value-added products that can be derived from agriculture waste. These include perfumes, flavouring agents, colouring agents, insect-repellents (Zakaria 2018), and raw material for paper making. Syn-gas produced during thermochemical conversion route can be used in production of fine-chemicals.

CONCLUSION

Agriculture waste generated annually is truly a 'resource', creating a variety of value-added products with applications in diverse fields like energy, environment protection, construction, cosmetics, pharmaceuticals, nutraceuticals etc. However 'waste-to-resource' is possible only if circular economy (CE) practices are adopted by masses at large scale including farmers, industrialists and consumers. To inculcate CE values and practices in society people are to be made aware about looming environmental crisis due to mismanaged waste and also regarding the benefits of recycling. Figure 14 presents an example of possible CE practices on agriculture farm. Further governments world-wide need to bring legislations in support of CE practices and a robust waste collecting system needs to be designed.



Source: Verma et al., 2012.

Figure 14. Possible circular economy (CE) model for agriculture farm.

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Chapter 10

THE ROLE OF NANOTECHNOLOGY IN WATER QUALITY MANAGEMENT AND WASTE WATER TREATMENT

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ABSTRACT

Water pollution, one of the mind-boggling issues that the whole ecosystem is concerned about, has increased the water quality crisis in every corner of the world. Industrialization initiated urbanization performs a massive role in contaminating water in several ways and eventually leads to deadly diseases. Water pollutants required efficient and continuous monitoring for better management and to ensure the availability of clean water. As the conventional methods have been proved costlier, researchers are focusing on nanotechnology for efficient management of water quality and reduction of the pollutants at a low expense. This chapter describes the role of nanomaterials as sensors for monitoring the water pollutants and the utilization of nanomaterials for the removal of contaminants. This review is also focused on the state-of-art sensing and treatment techniques utilizing various nanomaterials, including metals, metal-oxide, oxyhalide, carbon-based nanostructures etc. Besides, challenges and future aspects of engineered nanomaterials for environmental applications in wastewater management and treatment are also outlined.

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1. Introduction

The availability of clean water is considered as one of the major concerns of our era as it is essential for all living creatures for their survival. The enormous increase in urbanization leading to the expansion of slum areas, toxic industrial discharge, poor sewage system, polluted groundwater has uncountable effects on water quality. Approximately, 14000 people die every day of waterborne diseases caused worldwide due to the consumption of contaminated water. Some of the deadly diseases caused by water pollution are cholera (Pande et al. 2018), jaundice (Abbas et al. 2016), tuberculosis (Cohen & Mehta. 2007), dysentery (Pirsaheb et al. 2017), diarrhea etc. Factors like climate change, soil type, agriculture, mining, precipitation etc. also influence the water quality, but industries and municipalities have always been the greatest threats. In developed areas, the waste that predominantly includes municipal solid waste, industrial waste, agriculture waste, radioactive chemicals, heavy metals etc. is directly discharged into the water bodies like rivers, lakes, and oceans without significant recycling (Singh. 2001). The problem of contaminated water has spread across the whole world, and less than 1% of the earth's freshwater is available for drinking. Thus, it is imperative to monitor water quality to estimate nutrient or pollutant fluxes in water to ensure the safety of drinking water and resource recovery (Altenburger et al. 2019).

Conventional wastewater treatment removes solid organic waste through various physical, chemical, and biological techniques. It involves primary, secondary, and tertiary treatment (Figure 1) of the effluents followed by disinfection with the chlorine injection and proper storage facility to provide additional time for reclamation of the already treated water. But the use of this method is limited due to its poor treatment efficiency and high investment cost (Rajasulochana & Preethy. 2016). That is why researchers are continuously finding new approaches to eliminate these drawbacks.

Advances in nanotechnology have already made a big impact on the areas of chemistry, pharmacology and medicine, electronics and photonics, material science and environmental monitoring. Here, the size of the particles plays a vital role because of their high surface area to volume ratio and high reactivity. The use of nanomaterials in wastewater management could be the next-generation treatment system because of their efficient performance and cost-effectiveness as compared to the conventional one (Lu et al. 2016). Many countries across the world have invested in research programs and opened innovative centres focusing on wastewater treatment. Water quality index parameters like pH, dissolved oxygen, temperature, TDS, total coliform, heavy metal are also determined using nanosensors. Several different nanostructures have also been used for water treatment and its remediation. Some nanomaterials such as metal nanoparticles, metal oxide nanoparticles, carbon nanotubes, nanocomposites can act as catalysts and destroy the contaminants through oxidation, while others (polymer-based) as a filtration membrane that separates and isolates these contaminants (Kumar et al. 2014). Approximately 10% of the world's population is practicing untreated water for irrigation and fertilization purposes. It contains nutrients and dissolved organic matter essential for crop production but sometimes heavy metals are also found which are dangerous for human consumption and pose serious risks. Considering health benefits, contaminated water used in agriculture has pros and cons (Sankhla et al. 2018). Thus, it is also essential to manage and treat the wastewater, and supply the reclaimed water across the sector and borders. Different types of wastewater sources have different contamination levels, so source separation is also a way to keep water away from unwanted waste and retain a high volume of relatively safe water.

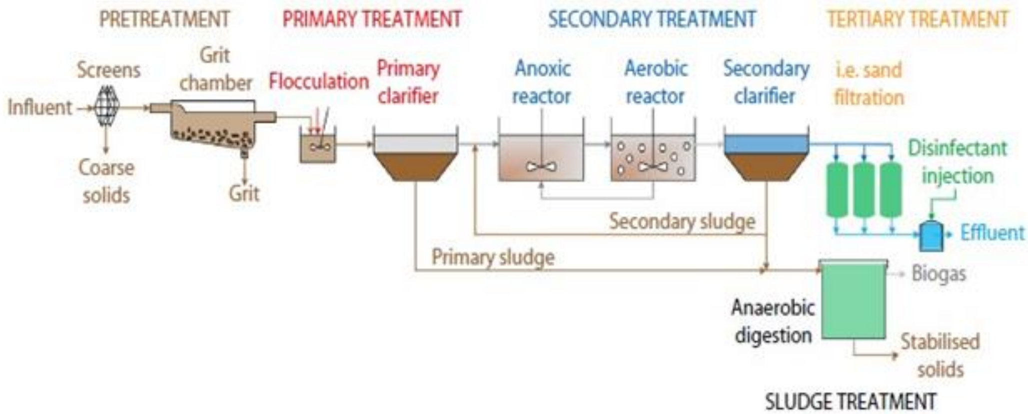


Figure 1. Flow diagram of different stages of wastewater treatment plants (Reproduced with permission from Suárez-Iglesias et al., Copyright©2017, Elsevier).

1.1. Water Scarcity and Quality

The global increase in population and its growth in various ways lead to a shortage of clean water resources. Around 1.2 billion people living in arid and semi-arid areas experience physical scarcity of water due to severe environmental degradation. Countries with high poverty issues are affected by the economic scarcity of water caused by underdeveloped water infrastructure despite the water abundance. In order to manage the water quality crisis, a water quality index (WQI) has been generated by collecting all the parameters to portray the reality of the water in just one number. The index was first developed by Horton in 1965. Since then many other researchers have also reported the index's calculation by considering different variables (Akter et al. 2016). The water quality parameters that have been considered for the calculation of the water quality index include heavy metal ions, total dissolved solids, pH, electrical conductivity, DO, BOD, COD etc. (Clesceri & Eaton. 1992) As per the recent WQI studies, the majority of the area falls under the category of good, moderate and poor quality of water suitable for drinking purposes; the rest is unsuitable and needs proper treatment. The Environmental Protection Agency of the United States has set up the maximum contaminant level, which is the highest value allowed in the public water supply. This value determines the contaminant level present in water with no adverse health effects.

1.2. Water Pollution and Its Causes

Although industrialization is considered as a boon for the entire world, it has also adversely intoxicated the environment by releasing various pollutants. In addition to that, it has initiated the migration of people from rural to urban areas resulting in overpopulation and pollution of land, air and water. Polluted water bodies have become the greatest problem today and pose a significant threat to the aquatic system and human lives.

Water pollutants are categorized based on their source and origin. The most significant sources are:

- Sewage system: It consists of wastewater discharged through residences, institutional, and public facilities. Sanitary sewage mainly contains fluids from kitchens, bathrooms, sinks and, human solid waste in the water. A network of underground pipes and pumping stations which flow to the wastewater treatment plant are arranged. However, sometimes the poor management causes the spilling of the sewage in various water bodies and polluting it. For managing mildly polluted water like rainwater, storm drainage systems are mostly connected to the tunnels directing towards the water bodies without any treatment. However, sanitary sewage needs systematic treatment as it is one of the main problems related to water pollution.
- Agriculture waste: Most of the pesticides and fertilizers used in cropping fields also contaminate our water bodies. Excess of nutrients such as phosphorus and nitrogen causes algal growth and their decomposition by aerobic bacteria consumes a lot of oxygen which eventually leads to its insufficiency for aquatic systems. Animal husbandry practices like feeding animals with the excess of heavy metal supplements such as, copper, zinc, arsenic, mercury to promote their growth causes a vast destruction of aquatic life.
- Industrial waste: Industrial wastes are primarily toxic, ignitable, corrosive or reactive, which adversely affect water quality if directly released into the environment. Generally, the industries manufacturing dyes, paints, drugs flush out toxic and organic pollutants into the water bodies. Some of the newest waste problems have been generated from nuclear power plants that deal with the chemical processes and generation of radioactive waste. These wastes have become major industrial wastes that cannot be destroyed and lose their activity only after a very long time.
- Oil pollution: A large portion of water is polluted by dripping off the oil and gasoline from large tankers and seeping from the ocean's bottom. Oil spreads over the water surface at a great distance and cause substantial damage by blocking the sunlight needed to all life forms for their survival. Also, it contaminates the water bodies, which cannot be used for drinking and other purposes.

1.3. Effects of Water Pollution on Human Health

Water pollution can adversely affect human health in two ways:

- Direct via bathing, swimming, drinking and inhaling the contaminated water that contains organic and inorganic impurities due to improper sewage treatment.
- Indirect via the ecosystem through the food chain by ingesting the vegetables and fishes grown in contaminated water.

Due to the increase in water pollution, waterborne pathogens also increase, causing deadly diseases among humans (Craun et al. 2006). Disease associated pathogens found in the contaminated water can be bacteria, virus or protozoa (Leclerc et al. 2002). Some of the bacterial pathogens like vibrio, *Salmonella, Shigella* species cause diarrhea and gastrointestinal tract related infections (Dougan & Baker. 2014), while others like *Mycobaterium* show symptoms related to respiratory infections (Smith. 2003). Viral pathogens like Hepatitis A, E virus, adenovirus, poliovirus, rotavirus, enterovirus and coxsackie virus not only cause the gastro infections but more severe illnesses like encephalitis, meningitis, hepatitis, and cancer (Hasbun et al. 2017). The most common parasitic protozoans are *Giardia* and *Cryptosporidium* causing giardiasis and cryptosporidiosis in human (Squire & Ryan. 2017). These pathogens are choline resistant and have become a significant concern among other pathogens. Other protozoans found in polluted water and cause human infection are *Toxoplasma gondii, Entamoeba histolytica, Cyclospora* species, *Blastocystis hominis, Acanthamoeba* species, *Sarcocystis* species etc. (Baron. 1996).

Contaminated water not only contains harmful microbes but also heavy metals, pesticides and nitrate fertilizers. Due to the shortage of pure water supply, most of our agriculture sector depends on low quality water for irrigation which destroys the crop and infects the whole production. Consumption of these infected products leads human lives into danger. Most of the heavy metals found in polluted water bodies such as: As, Cu, Cd, Pb, Zn, Hg, Ni and Cr, and are feared to cause associated poisoning (Tchounwou et al. 2018). One of the most cited diseases, “Minamata disease,” was caused due to the consumption of contaminated fishes. Methyl mercury discharged from chemical fertilizer manufacturing factories contaminated the water and caused illness in the locals of Minamata, Japan in 1956 (Harada 1995). Long-term exposure to arsenic can cause gastrointestinal tract related problems and other symptoms of polyneuritis.

2. Analytical Methods for Water Quality Measurement

Due to the escalated growth in industrial and agriculture fields, related pollutants have also increased enormously in the aquatic ecosystem. Thus, proper identification and continuous monitoring are required. Some of the analytical techniques used for the environmental monitoring and water quality determination are as follows:

2.1. Colorimetric Sensors

Colorimetric sensors are optical sensors that change their color as a result of any physical or chemical environment changes. It is the most commonly used technique due to its ease of use, low cost, and sensitive and selective response toward various analytes. Its working principle is based upon Beer-Lambert law, which explains that the absorption and transmittance of light through a sample depends on its concentration. A beam of light passes through the sample, and transmitted colored light is measured. These sensors are applied in screening water for harmful chemicals like chloride, fluoride, cyanide hydrazine etc.

2.2. Fluorescence-Based Sensors

This phenomenon occurs when a loosely bound electron in an atom absorbs the energy from a photon and gets excited to a higher energy state, and loses energy in the form of light while returning to its ground state. Not every molecule involved in excitation and return results in fluorescence emission; it only happens when it partially dissipates the energy of the excited state to yield the relaxed singlet excited state before returning to the ground state. Here, non-radiative relaxation and fluorescence quenching exploit the effects that prevent fluorescence from happening (Figure 2). Due to the energy sharing and unpaired electron structure of the carbon ring, organic compounds provide good fluorescence effects. The detection of algal pigments, dissolved organic matter, hydrocarbons, antibiotics in the water bodies are possible with this method (Neupane et al. 2016).

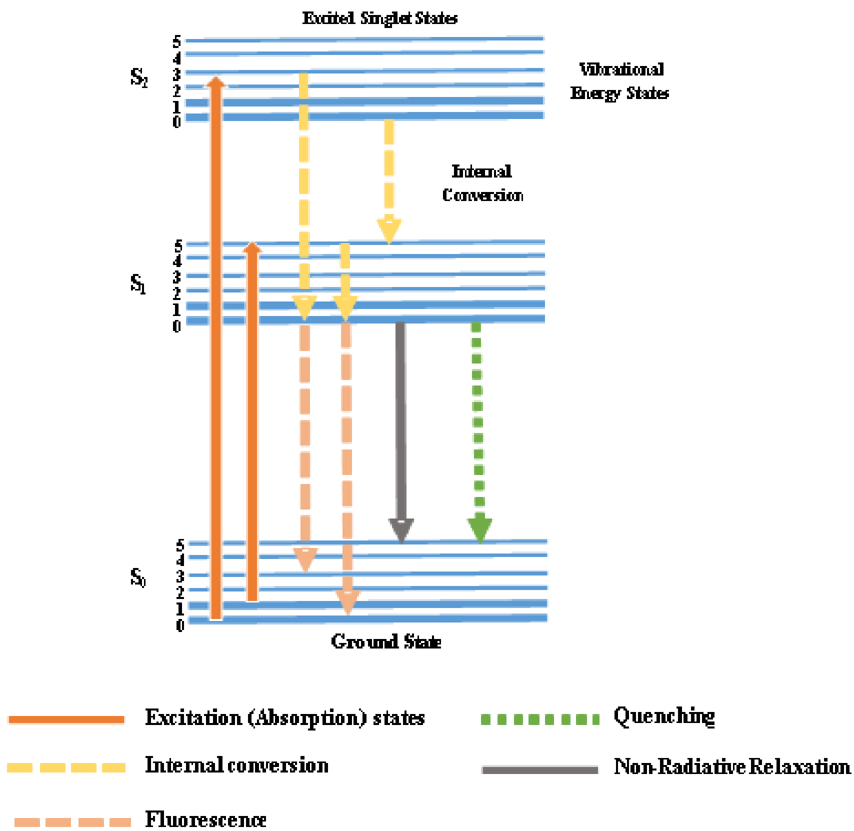


Figure 2. Jablonski diagram showing the energy state transitions leading to fluorescence and non-radiative decay to the ground state.

2.3. Atomic Absorption Spectroscopy

It is a high throughput technology used to analyze compounds in solution. Here, the analyte in the solution absorbs a particular wavelength and emits accordingly, and this emitted light is the characteristics of that analyte. This method follows the Beer- Lambert law, where the absorbance is directly proportional to the concentration (Menzies. 1960). It has an immense application in the analysis of trace metals (at very low level) in various water bodies and industrial effluents (Pourjavid et al. 2014). AAS has an unlimited application and is still a popular choice in the field of environmental monitoring. Some of its types that have been found relevant for the detection of heavy metal ions are:

2.3.1. Flame Atomic Absorption Spectrometry (FAAS)

This technique is used to determine the lowest concentration (ppm/ppb) of the trace elements. In high-temperature flame, where these metal ions are sprayed, they get reduced to their atoms and absorb light from an element-specific hollow cathode lamp. Despite of being a robust technique, it has a drawback that it is capable of measuring only one atom at a time.

2.3.2. Graphite Furnace Atomic Absorption Spectrometry (GFAAS)

Here, a narrow carbon tube is used to atomize the sample in order to reduce the spectral noise generated because of flame. It has the detection limits lower than ppb levels making it highly sensitive AAS technique.

2.4. Electrochemical Sensors

These sensors convert electrochemical reactions occurring between the electrode and the analyte into an electrical signal and are widely applied to measure pH, dissolved oxygen, and other ionic species.Many of them are designed for sensitive and selective detection of ions and pathogens (Pujol et al. 2014). The three major types of electrochemical sensors are:

- Potentiometric sensors
- Amperometric sensors
- Conductometric sensors

2.4.1. Potentiometric Sensing Method

This technique measures the potential difference between the indicator electrode and the reference electrode under zero current flow. Moreover, the resulting potential difference gives information about the composition of the sample. The electrodes generally used as reference electrodes are standard hydrogen, silver chloride, and calomel, whereas the indicator electrodes are mostly glass and metal ion electrodes. The salt bridge is used to prevent interference in the reference electrode generated due to the analyte. There are three types of potentiometric devices:

- Ion selective electrodes
- Coated wire electrodes
- Field effect transistors

2.4.2. Amperometric Sensing Method

This technique uses working and the reference electrode where the current flows between them are measured at a single applied potential. Also, it has a subtype where the current is recorded for varying potential differences, known as voltammetry. Here the reference electrode always has a steady potential.

2.4.3. Conductometric Sensing Method

This technique involves electrodes made up of conducting material whose conductivity gets affected upon adding the target analyte. This setup does not require any indicator and reference electrode.

2.5. Chromatography

This separation technique is mostly used in chemical laboratories for analysis, isolation, and sample purification. These separations can only be accomplished if there is a high difference in sample interaction for the two phases. The water quality monitoring agency uses this technique to analyze the purity of water and trace the contaminants.

2.5.1. GC-MS

This technique combines the working of both gas chromatography and mass spectrometry. This technique has an application in environmental monitoring to identify and quantify the chemicals present in water (Loos et al. 2017). GC-MS data acquisition can be performed either in full scan for qualitative analysis or selected ion monitoring to get the quantitative data. Using this technique, many contaminants have been determined including pesticides, organic compounds, metal ions etc.

2.5.2. HPLC

Separation through this technique is based on the interaction of the analyte between the stationary and mobile phases. The greater interaction of the analyte with the stationary phase results in a longer retention time. The traces of Ni(II), Co(II), Cu(II), Se(IV), and Cr(VI) ions in an aqueous solution have been determined using HPLC (Okano et al. 2015).

2.5.3. Ion Chromatography

Ion chromatography is considered as a precise and convenient method for determination of various organic and inorganic species present in the water bodies. The separation through this technique is based on the interaction between the resin and the ions. Ionic species gets absorbed while running through the ion exchange column and get eluted with the help of a particular eluent. In this way, the ionic concentration can be determined by calculating their different retention time. For the detection, some of the detectors used in combination with ion chromatography include conductivity detectors, electrochemical detectors and spectroscopic detectors. Among all, conductivity detection is mainly applied due to the presence of charged species. And the detection depends on the difference between the conductivities of ionized species present in it. Due to the use of pharmaceuticals in medicines and as food additives, these chemicals have been known to be present in sewage effluents. Ion chromatography has an immense application in water analysis for these kinds of pollutants. Anions like nitrate, sulphate, cyanide, bromated, iodide, perchlorate, trifluoroacetic acid, chromium can be determined using this technique in the parts-per-billion range (Nakatani et al. 2012).

3. Nanotechnological Approach for Water Quality Management

Nanotechnology is a new expanding area of science that deals with nanosize materials with a high surface area to volume ratio. It involves top-down reductive approaches and bottom-up additive approaches for manipulating structures at nanoscale dimensions. The renowned physicist "Richard Feynman" in one of his meetings, talked about his ideas and concepts by emphasizing, "There's Plenty of Room at the Bottom" and shed some light on the field of nanoscience. Later, this emerging technology found applications in various fields like electronics, medicine, textiles, cosmetics, and environment. Nowadays, the scientists are working on modifying conventional treatment and sensing assays with the help of nanostructures for further refinement in flushing out the contaminant from the environment. Several techniques based on nanostructures are discussed below which are used as sensors for the detection of organic and inorganic waste in water for further treatment.

3.1. Noble NPs Based Colorimetric Sensing

New advances in the field of nanotechnology have modified the colorimetric sensing of contaminants using noble metal nanoparticles. The frequent use of metal nanoparticles made of gold and silver is because of their exceptional localized surface plasmon resonance bands. Localized surface plasmon resonance phenomenon plays an influential role in metal nanoparticles based colorimetry due to the oscillation of free electrons in the conduction band upon interaction with light. Hence, the nanoparticles exhibit different colors depending upon their shapes and sizes. In one study, the detection of Ni^{2+} ions in wastewater was done through colorimetric sensing assay using citrate-stabilized silver nanostructures of size 10.4 ± 4.5 nm. A change in color from yellow to orange was observed due to the aggregation of nanoparticles because of Ni^{2+} ions in tap water (Almaquer et al. 2019). There are numerous reports on colorimetric sensing assay using gold nanoparticles to detect Hg^{2+} and Pb^{+} ions. AuNPs-NDTM of spherical shape with 29 ± 7 nm based Pb^{2+} ions detection resulted in a color change from pink to violet in commercial paints (Sengan et al. 2020). Nanomaterials synthesized through both biological and chemical methods have been used as nanosensors to detect toxic heavy metals. Biologically synthesized metal nanoparticles were also employed in sensing of various ions such as Pb^{2+}, Ca^{2+}, Hg^{2+}, $Zn^{2+}$and Cu^{2+} (Annadhasan et al. 2014). In the presence of Hg^{2+}ions, the aggregation of gold nanoparticles (AuNPs) induced by 4-mercaptophenylboronic acid (MPBA) got inhibited (Zhou et al. 2014). The detection of Hg^{2+} ions was observed resulting in a visible color change of the AuNPs solution from blue to red (as shown in Figure3).

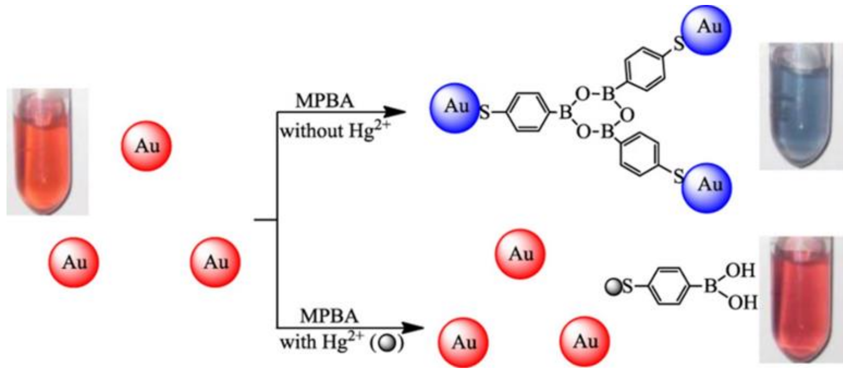


Figure 3. Colorimetric sensor of mercury ions has been presented based on anti-aggregation of gold nanoparticles via self-dehydration condensation of boronic acid. (Reproduced with permission from Zhou et al., Copyright©2014, Elsevier).

3.2. Quantum Dot Based Sensing

Quantum dots are nanosized semiconductor particles of 2-10 nm in diameter which emit distinctive colors upon hitting by some excitation source. These materials are made up of Zinc sulfide (Wang et al. 2008), lead sulfide (Mitri et al. 2020), indium phosphide, and most commonly used cadmium selenide (Subramaniyan & Veerappan. 2019). They are manufactured through various methods like colloidal synthesis, chemical vapor deposition. So, when their size progressively decreases, the band gap increases simultaneously between the highest valence and lowest conduction band. It involves a lot of energy needed to excite the dot and when it returns to its ground state it releases a great amount of energy resulting in fluorescence. Depending upon their size, the large nanocrystals produce longer wavelengths and vice versa. These dots possess various properties not only because of their size but also shape and composition they have.

Due to their characteristic fluorescence feature, QDs have many applications in electronic devices (Schaller & Klimov. 2004), medical imaging (Jin et al. 2011) and environmental monitoring (Long et al. 2020). For water quality assessment, these dots can be used to detect various targets like pathogens, metal ions, pH etc. Recent studies showed that the use of semiconductor quantum dots have bypassed the disadvantage of the fluorescent dyes in the biological specimen (Law et al. 2009). Moreover, the use of QDs as passive fluorescent has been discussed in many papers. Ligand-conjugated QDs help not only in the solubility of QDs but also participate in response to metal ions. The usefulness of the thiol ligand was successfully demonstrated for the detection of Hg^{2+} and Pb^{2+} ions (Gonzalez & Carrion. 2014). For example, fluorescent carbon dots are synthesized for the selective detection of Pb^{2+} ions as shown in Figure 4 (Kumar et al. 2017). Through this phenomenon, heavy metal ions can be detected as they quench the fluorescence emitted through the QDs by absorbing the released energy of the electron transition. Various metal oxide quantum dots have also been used for the quantification of metal ions at the ppb level. The most innovative bioinspired QD-based sensors are also used in heavy metal ions analysis and pathogen detection (Mohamadi et al. 2017).

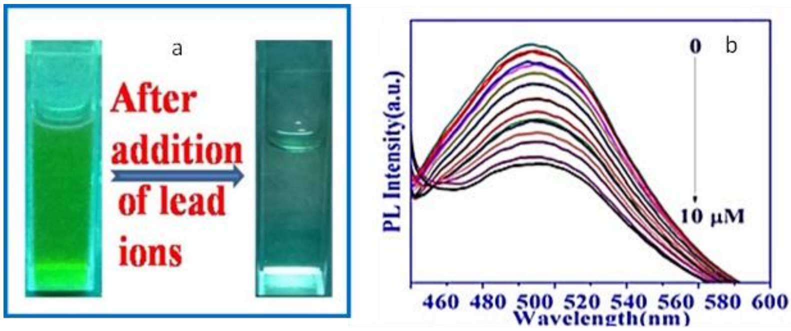


Figure 4. Fluorescent Carbon QDs before and after addition of Pb^{2+} ions:(a) Fluorescence images of visual detection of trace Pb^{2+} ions. (b) Decreases of thefluorescence intensity after addition of the different concentration lead ions. (Reproduced with permission from Kumar et al., Copyright©2017, Elsevier).

3.3. Immunochromatographic Strip Based Sensing

This technique is based on the capillary action and is somewhat similar to ELISA. It combines chromatography (separation of sample components based on their movement through sorbent) and immunological reaction. This strip assay involves the use of metal nanoparticles coated antibodies for the detection of ions and microbes. This strip generally consists of four components, viz. sample application pad, conjugate pad, nitrocellulose membrane, and adsorbent Pad.

Colloidal gold nanoparticles probe-based IC strip is a rapid and highly sensitive technique for detecting heavy metal ions. In one of the study a gold nanoparticle-labelled antibody, anti-Cd-1-(4-isothiocyanobenzyl) EDTA(ITCBE), is used against Cd-ITCBE (as shown in Figure 5)observed to have a detection limit of approximately 5ng/ml for Cadmium ions (Song et al. 2018). Likewise, IC strip assays have also been developed to detect microbes using gold nanoparticles coated specific antibodies against their antigen (Cho et al. 2015). The detection of diphtheria toxin, AuNPs coated with the antibodies specific for fragment A was observed to have a detection limit of 0.5 ng/ml (Engler et al. 2002).

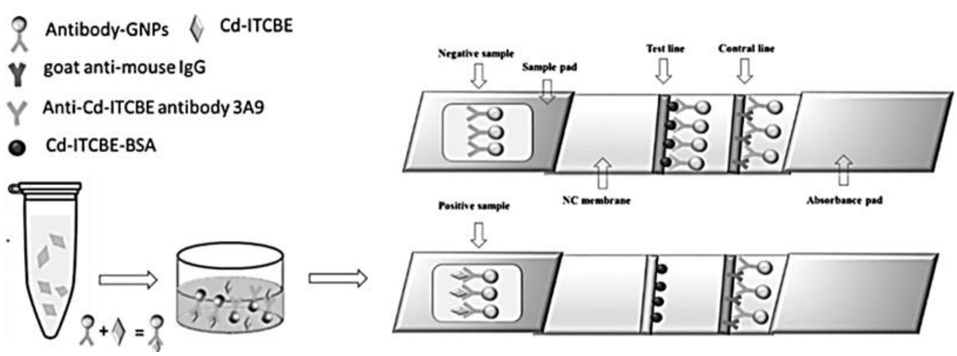


Figure 5. Immunochromatographic assembly for cadmium ion detection using AuNPs conjugated anti-Cd-ITCBE antibody. (Reproduced with permission from Song et al. 2017).

3.4. Electrochemical Sensing

The electrochemical sensors can produce electronic outputs in digital signals by measuring current, conductivity, potential, and resistance through them. Nanotechnology, in association, made it more precise for detection by acting as an interface. Several nanomaterials such as metal oxide nanoparticles (Krasovska et al. 2018), carbon nanotubes (Jiang et al. 2018), graphene oxide (Gong et al. 2014), molybdenum disulfide nanosheets (Wang & Mi., 2017) etc. have been used as a nanointerface in electrochemical sensors. These nanointerfaces improve the electron transfer rate of electrochemical cell setup and provide a large surface area to volume ratio to immobilize specific biomolecules. Generally, nanostructures of 1-100 nm in diameter used for various electrochemical sensors were developed to avoid the toxic effects of contaminants (Karim et al., 2020). Certain studies on electrochemical sensors have been reported to detect pathogens, pesticides and heavy metal ions in the water. The detection of heavy metal ions (e.g., As^{3+}, Hg^{2+}, Cd^{2+}, Pb^{2+}, Cr^{6+}etc.) becomes possible because metal oxide nanoparticles are used as an interface as they offer good stability, electrocatalytic activity, and good adsorption ability (Lee et al. 2016). For example, Aswathi et al. used exfoliated molybdenum disulfide for the electrochemical sensing of Hg^{2+} ions (Figure 6). The detection limit (LOD) was extremely low (0.000001 nM), which satisfactorily meets the sensitivity requirement of the U.S. Environmental Protection Agency (EPA) (Aswathia and Sandhya, 2018). A molecularly imprinted electrochemical sensor functionalized with 4-vinyl benzoic acid and graphene was developed to detect thiamethoxam (TMX), a pesticide (Xie et al. 2017).Other metal oxide modified electrodes were also fabricated for the detection of nitroaromatic pesticides.

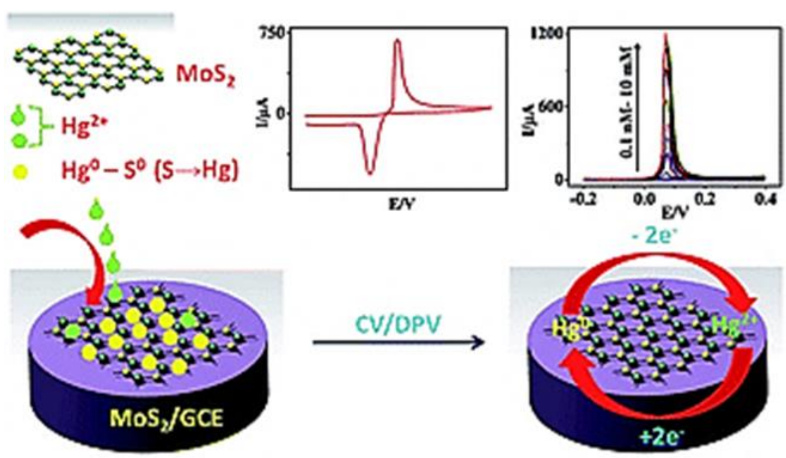


Figure 6. The schematic representation for the electrochemical detection of Hg^{2+} at the MoS_2 modified GCE. (Reproduced with permission from Aswathia and Sandhya, Copyright©2018, Royal Society of Chemistry).

3.5. Raman-Based Sensing

Raman scattering involves the inelastic scattering of photons where the incident and scattered frequency of photons differ, depending upon the chemical structure of the analyte.

Inelastic scattering is the effect of Stokes and anti-Stokes scattering pattern (Figure 7) where there is a decrease and increase in the resulting frequency, respectively. The molecules are mainly in the ground state at room temperature, due to which only Stokes scattering patterns are usually found and considered for Raman measurements (Smith and Dent, 2005).

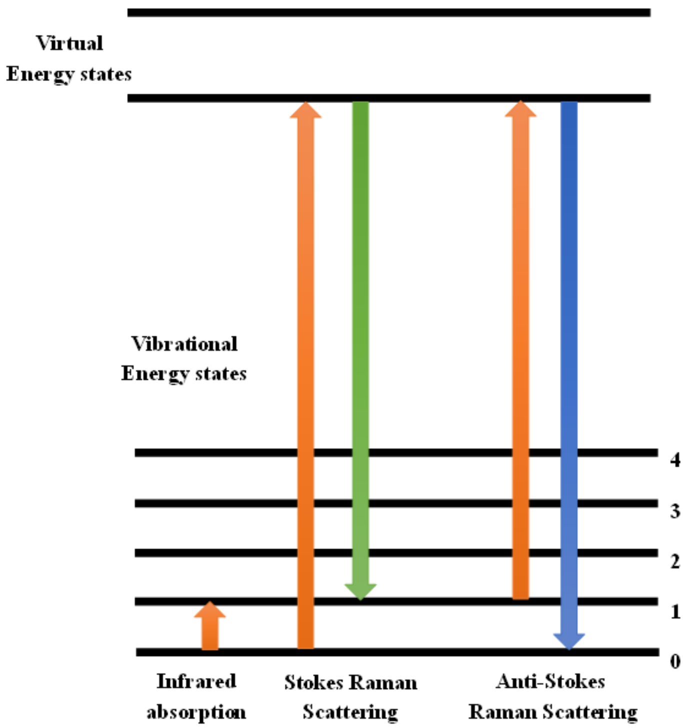


Figure 7. Energy level diagram related to Raman scattering.

Figure 8 describes the four major components used in the Raman spectroscopy are as follows:

- Excitation source
- Illumination and light collection optics
- Wavelength selector unit
- Detector

In the most recent development, the limit of detection (LOD) in Raman technique has improved by reduction of background noise and enhancement of scattering intensity. Some of these advanced techniques involve surface-enhanced Raman scattering (SERS) and time-gated Raman spectroscopy. SERS greatly enhances the Raman signals from the target molecules adsorbed onto the surface of a substrate. The chemically bonded target analyte onto the metal substrate exchanges electrons with them and gives rise to the additional enhancement in intensity amplification. Currently, approaches have been undertaken to apply SERS in water quality monitoring as it detects very low concentrations (Kneipp et al. 1997). Nanofabrication technology, such as nanosphere (Stiles et al. 2008) and electron beam lithography (Hatab et al. 2008) has been developed for modifying SERS instruments with nanoparticles. Generally, silver and gold nanoparticles are used as they have a strong ability to excite intensive plasmon resonance. SERS sensors based on nanomaterials have been demonstrated in many reports as an effective tool for low concentration detection of contaminants are given below Table 1. For the detection of various organic pollutants, pesticides, gold nanoparticles deposited on the surface of polydopamine (PDA) were synthesized as a porous nanowaxberry (Figure 9) with a detection limit of 1ppm and used against the target analyte (Chen et al. 2018). In one of the reports, reversal of the bismuthiol II-induced aggregation of AuNPs was observed with a remarkable change in color and Raman shift as soon as Hg^{2+}ions were introduced (Duan et al. 2012). Those Bismuthiol II–AuNPs could be used to detect Hg^{2+} ions in level in a water sample (Figure 10).

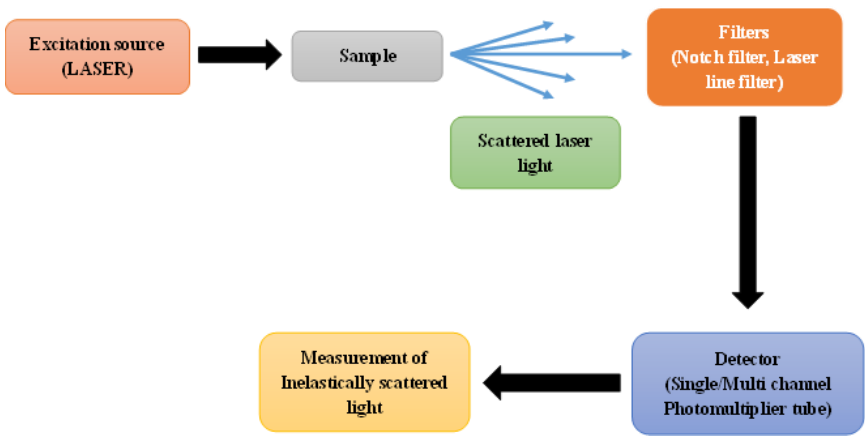
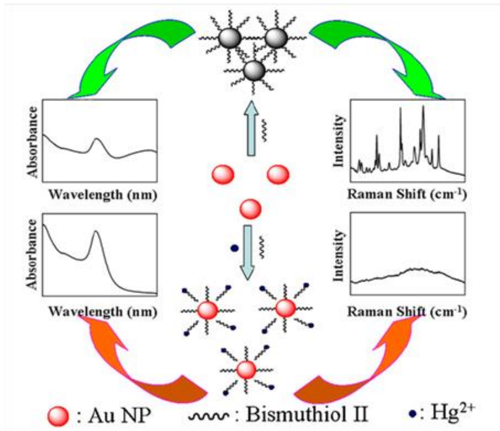


Figure 8. Basic Raman spectroscopy set up.

Figure 9. Schematic illustration of the synthesis process of polydopamine @ gold (PDA @ Au) nanowaxberry and its SERS detection. (Reproduced with permission from Chen et al.).

Some researchers from Technical University at Berlin developed SERS-based sensors to detect the contaminants like polycyclic aromatic hydrocarbons (PAHs) in the seawater caused by ships (Schmidt et al. 2004). Sometimes the incoming optical signals and detectors generate noises that interfere with the results. So, time-gated Raman spectroscopy comes into play to rectify the signal-to-noise ratio (Knorr et al. 2010). It involves two techniques Kerr-gated Raman system and fast time-gated Raman system. Kerr gated are optical shutters for incoming optical signals, and fast time-gated is used to modulate the detector.



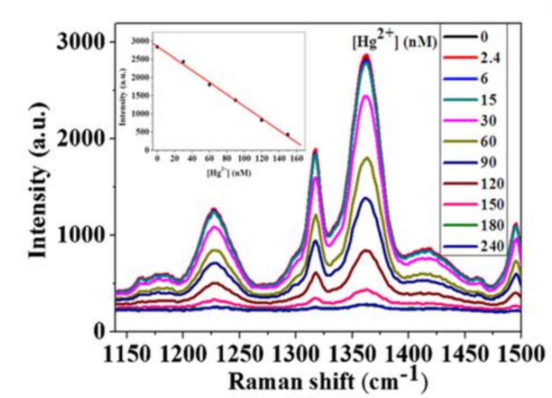


Figure 10. Sensing mechanism of the BismuthiolII–AuNPs as a dual-signal sensor for Hg^{2+}detection and SERS spectra of Bismuthiol II–AuNPs with different concentrations of Hg^{2+}. (Reproduced with permission from Duan et al.).

Table 1. Some of the SERS substrate used in the detection of various contaminants in water

S. No.	Sample	SERS Substrate	Limit of detection	References
1.	Arsenic	FeOOH doped dendritic Ag nanostructures)	10^{-10}M	Pradhan et al. 2015
2.	Cyanide	Ag nanoparticles	2.7 $\times 10^{-7}$M	BurmaKyong et al. 2005
3.	RDX in water	Au nanoparticles	1 $\times 10^{-6}$M	Hatab et al. 2010
4.	*E. coli*	Ag nanosculptures thin film	1.5 $\times 10^{2}$ cfu/ml	Srivastava et al. 2015
5.	*B. subtilis*	Au nanoparticles	2.5$\times 10^{-14}$M	Cheng et al. 2011
6.	Uranium	APA-modified gold nanoparticles	8$\times 10^{-7}$M	Ruan et al. 2007
7.	Rhodamine 6G	Au nano films	10^{-11}M	Wang et al. 2020

4. Nanotechnological Approach for Waste Water Treatment

4.1. Nanoadsorption

Nanoadsorbents (or nanosorbents) possess vast properties such as excellent adsorption ability, making them a powerful wastewater treatment approach. Finding these nanosorbents at the commercial level is very difficult. To overcome this problem, scientists now focus on producing the nanosorbents in huge quantities at the commercial level (Salim, and Ho 2015). The mechanism for the removal of water pollutants by nanosorbents is shown in Figure 11. Generally, nanosorbents reported in the literature are based on carbon or its allotropes like carbon black, graphene oxide and graphite. However, metal or metal oxide and polymeric nanosorbents are also reported in some literature (Yu et al. 2017). The most potent nanosorbents to remove the toxicity in the wastewater process are the composite of different materials, e.g., Ag/carbon, Carbon/TiO_2, Ag/polyaniline etc. Carbon nanotubes (single-walled and multi-walled) have sustainable surfaces for adsorption due to the higher surface area. They have hydrophobic surface properties which help in preventing the aggregation by reducing the active surface sites. These surface adsorption properties make carbon nanotubes an efficient and promising material in the removal of pollutants. Dendrimers have also shown satisfactory results for eliminating organic pollutants and heavy metals from the wastewater (Fuwad et al. 2019). With the help of dendrimers, copper ions were reduced using an ultrafiltration system (Shen et al. 2014). Zeolites are another important nanosorbent in which many nanoparticles such as silver, copper ions can be embedded. Zeolites can control the number of metals and also act as antimicrobial agents.

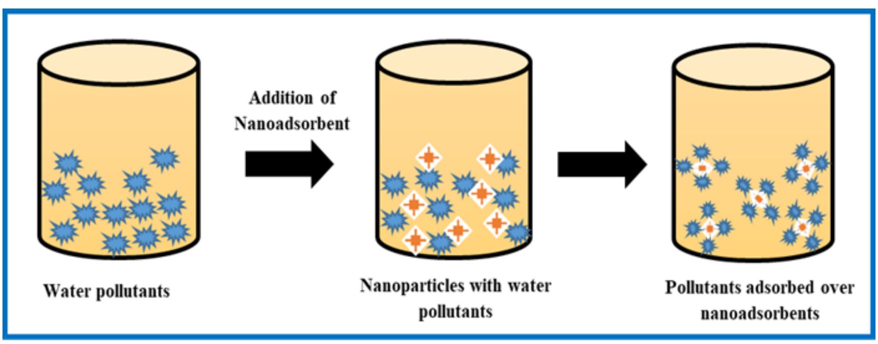


Figure 11. Mechanism showing Nanoadsorption process for the removal of water pollutants from the water.

Furthermore, magnetic nanosorbents also play an essential role in water treatment, and they can remove various types of organic pollutants from the water (Sahebi et al. 2019). Magnetic nanosorbents are synthesized by specific ligands coated with magnetic nanoparticles for their high affinity (Perez et al. 2019). Many methods, such as magnetic forces, ion exchange, cleaning agents etc. have been reported to regenerate these nanosorbents, and the regenerated nanosorbents are cost-effective and can be used at the commercial level. Some toxic effects are related to the nanosorbents morphology, chemical stabilizers, and surface modifications reported in the literature. Further attention is going towards in synthesizingmore stable, shape and size nanosorbents to overcome the toxicity effects (Manikam et al. 2019). Bioadsorbents could replace chemically synthesized nano-adsorbents due to their high biodegradable, biocompatible, and nontoxicity properties. Graphene oxide is an emerging nanomaterial used as a nanoadsorbent to remove many pollutants and gives more stable results than others due to its excellent properties.

4.2. Nanomembrane Based Filtration/Nanofiltration

Nanomembranes are unique membranes made with different nanofibers and utilized to eliminate undesired nanoparticles present in the aqueous phase. The process takes place at a high elimination speed with condensed fouling capacity, and it also serves as a pre-treatment process used for reverse osmosis (Jhaveri and Murthy 2016). Many studies on membrane nanotechnology have been reported to produce multifunction membranes using different types of nanomaterials in the different polymer-based membranes. For instance, nanofiltration, reverse osmosis, ultrafiltration can be done using water porous membrane. This membrane consists of porous support with the composite layer. However, the composite layer is majorly carbon-based material such as graphene oxide or CNT dispersed into the polymer matrix and provides foul resistance and aqueous transport. Carbon nanotubes have antimicrobial properties that minimize fouling and biofilm formation, and reduce mechanical failure chances (Hogen-Esch et al. 2019). Silver metal particles with higher antimicrobial properties are doped with a polymer to produce a polymeric membrane to prevent microbes and biofilm inhibition on the membrane surface. It worked for the inactivation of viruses and the prevention of biofouling (Saleh et al. 2019; Ronen et al. 2015).

There are some significant challenges in the use of nanomembrane, like membrane clogging and membrane fouling. To overcome this problem, super hydrophilic nanoparticles are added to make a thin film nanocomposite membrane that can prevent clogging and fouling. Other approaches for overcoming membrane clogging and fouling are metal oxide nanoparticles such as TiO_2, Al_2O_3, and antimicrobial nanoparticles (nanosilver, CNTs) are used due to their high hydrophilicity, high porosity, and good fouling resistance. Nanomembranes are also used for wastewater treatment (Figure 12) because they have high uniformity, homogeneous ability, optimization, minimum time required, and handle easily (Hirata et al. 2019). Nanophotocatalysts can be introduced in the nanocomposite membrane for the degradation of organic pollutants. For example, TiO_2 metal oxide incorporated nanomembranes and films are mainly used to inhibit the growth of various microorganisms and organic pollutant degradation (Gopalakrishnan et al. 2018). The growth and the development of the nanotechnology field produced several nanostructured catalytic membranes that have novel or unique properties such as improved selectivity, higher decomposition rate, and higher foul resistivity (Liu et al. 2017; Shetti et al. 2019). The incorporation of nanostructured catalytic materials such as iron-catalyzed based free radical and enzymatic catalysis within the pore membrane showed valuable progress in this technology. So, it is possible to carry out oxidative reactions to remove pollutants and detoxify water without using toxic chemicals. The efficiency of nanostructured catalytic membrane for industrial applications is checked using immobilized membrane nanoparticles (metal oxide like iron oxide) to react with hydrogen peroxide (H_2O_2) to form free radicals ions, which can be used for the removal of chlorinated based organic pollutants in the groundwater. The nanostructured materials are still handy in various other environmental applications (Ibrahim et al. 2016). Several studies of immobilization of metallic nanoparticles on the membrane (e.g., cellulose acetate, chitosan, polysulfones etc.) have been reported for the degradation of a toxic substance. They also contain unique properties such as hindrance of nanoparticles, high reactivity, absence of agglomeration, and surface reduction (Mekaru et al. 2015; Jawed et al. 2020). Palladium acetate and polyetherimide were used for the preparation of nanocomposite films. Novel type interactions are present among hydrogen and Pd nanoparticles which increase the water treatment efficiency (Umar et al. 2016). Moreover, the growing nanotechnology field produces many significant catalytic membranes with high selectivity, better permeability, and higher fouling resistance. Currently, hybrid and bottom-up approaches are emerging due to their multifunctional characteristics in wastewater treatment (Abdullah et al. 2019). Advantages of using nanomembranes for the treatment of wastewater are:

- The primary purpose of using nanomembranes is to separate toxic particles from the water and make water drinkable.
- With the help of nanomembrane filters, water safety level can be measured (Bhat et al. 2018).

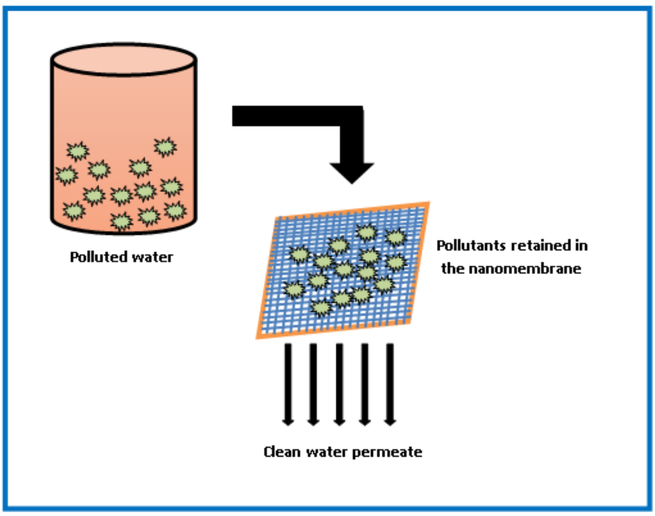


Figure 12. Schematic presentation of the Nanomembrane filtration mechanism.

There are also some limitations or disadvantages related to the nanomembranes:

- Using a membrane a few or more times, the fouling issue comes which is the central issue and makes the approach expensive and inefficient.
- This fouling issue occurs in the nanomembrane under higher working conditions. In some cases, the conditions are not appropriate, such as overpressure, temperature, and optimization are responsible for the membrane fouling (Rashidi et al. 2015).
- Membrane stability is another main limitation. Nanomembrane is unable to keep the stability for a long time. After some time, the stability starts reducing its efficiency

and the membrane does not give satisfactory outcomes. Frequent changing of nanomembrane to get excellent results will also cause other issues like high cost, the chance of impurity etc. (Belloň et al. 2019).

4.3. Water Disinfection

Apart from having excellent catalytic and adsorption properties, some of the nanomaterials have great antimicrobial activity. These materials include silver nanoparticles, chitosan, titanium dioxide, carbon-based nanomaterials (fullerene and carbon nanotubes etc.).

There are several reasons for using nanomaterials in the process of water disinfection:

- Direct action on bacterial cells to disrupt their electron transport chain flow.
- Can break the cell membrane.
- Oxidation of cellular compartments
- Produce hydroxyl radicals or reactive oxygen species.
- The formation of dissolved metal ions could cause damage to cellular organelles (Li et al. 2008).

Table 2. Antimicrobial mechanism of different Nanomaterials

Nanomaterials	**Antimicrobial mechanism**
Silver	Protein damage, block DNA replication, membrane disruption
Titanium dioxide	Reactive oxygen species (ROS) production
Zinc oxide	Release of Zn^{2+} ions, production of ROS, Membrane disruption
Magnesium oxide	Membrane disruption
Fullerenes	ROS production
Carbon Nanotubes	Membrane disruption, Oxidative stress
Graphene nanomaterials	Membrane disruption, Oxidative stress

However, there are some limitations of wastewater disinfection processes using nanotechnology approaches. Some nanomaterials such as carbon nanotubes need to be strongly associated with the membranes of bacteria, viruses etc. for their disruption. So, attaching to the reactive surface is a must for the nanomaterials in the water disinfection processes. Subsequent antimicrobial activity cannot be observed using nanomaterials, such as using chlorine in conventional methods (Ayanda and Petrik 2014). The low cost is the advantage of the traditional disinfection procedures. Standardization is more competitive in the nanotechnological processes. The Antimicrobial mechanism showed by various nanomaterials is described in Table 2.

4.4. Nanophotocatalysts

The “photocatalysis” word comprises of two Greek words, “photo” and “catalysis,” which mean compounds decomposition in the presence of light. Usually, a substance or compound gets stimulated or activated in the UV/Visible or sunlight in this process

(Saravanan et al. 2017). Photocatalyst changes the rate of the reaction without their involvement during the chemical process. The main difference between traditional thermal catalyst and photocatalyst is that the former is activated through the heat while the latter is activated through the light energy photons (Gomes et al. 2019). Nanophotocatalysts are generally used for the purification of wastewater. They increase the reactivity of catalysts due to their higher surface area (Chen et al. 2019). It has also been reported that nanophotocatalysts can expand the oxidation ability due to the production of oxidizing species at the surface of the material that helps in the degradation of pollutants from the polluted water (Gómez-Pastora et al. 2017). Zero-valence based metal nanoparticles, semiconductor nanoparticles etc. are used mostly to treat environmental pollutants such as organochlorine pesticides, nitroaromatics, azo dyes etc. (Samanta et al. 2016). In the literature, many reports show that TiO_2 based nanotubes can be used very effectively to remove organic pollutants such as Congo Red, azo dyes, phenolic compounds, toluene, trichlorobenzene etc. from the wastewater (Qu et al. 2013; Raliya et al. 2017; Bhatia et al. 2017). However, the most common and widely used metal oxide nano photocatalysts are ZnO, SiO_2, TiO_2, Al_2O_3 etc. (Sherman 2003; Bhanvase et al. 2017). TiO_2 is one of the best photocatalysts from all materials used due to its low cost, toxic-free, stability, and easy availability on the earth's surface. Anatase, rutile, and brookite are the three states of TiO_2 found in nature. Among three, anatase is considered as an excellent nanophotocatalyst (Yamakata and Vequizo 2019).

However, another photocatalyst like ZnO is also used to eliminate wastewater contaminants and be reusable (Di Mauro et al. 2017). Cds/TiO_2 composite nanomaterial as a catalyst under the visible light irradiation can be used to degrade substances like dimethyl sulfoxide for the evaluation of the photocatalytic performance of the wastewater are also reported (Li et al. 2014). Other nanomaterials like iron-doped have the good ferromagnetism ability, which helps in reuse and easy recycling of the photocatalyst (Serrà et al. 2020). High photocatalytic reactivity Palladium incorporated ZnO nanomaterial is used for *Escherichia coli* removal from the wastewater (Berekaa 2016). The new and modern efforts focus on the metal oxides to increase the photocatalytic performance undervisible light irradiation by modifying them with other elements such as metal or metal ions carbonaceous-based materials, dye sensitizers, and many others. The researchers have also tried to decrease the band gap of nanophotocatlysts so that visible light-driven photocatalysis can be used to purify wastewater. In such an attempt metal-doped CeO_2 nanoparticles have been used as a photocatalyst to degrade different dyes present in water. Use of Mn-doped and Sr-doped CeO_2nanoparticles for the photocatalytic degradation of various azo and anthraquinone dyes have been reported in the literature (Ali et al. 2018). However, there is still a requirement for modifications in making promising photocatalysts (Umar et al. 2015; Malik et al. 2014). The nanophotocatalysts process occurs in two states homogeneously or heterogeneously. The most thoroughly studied state in modern time is heterogeneous nanophotocatalysts because it has excellent water decontamination and environmental applications. Generally, the word "heterogenous photocatalysis" is applied where light-based semiconductor photocatalysts are used to interact with liquid or gaseous phase (Kohtani et al. 2019). These photocatalysis-based applications strongly depend on the scaled-up reactor based on the developed designs. The most crucial task in reactor designing is illuminating nanocatalyst and optimizing mass transfer, especially in the liquid phase.

Furthermore, now more efforts are focused on the progress of solar photoreactors (Sundar and Kanmani 2020; Chong et al. 2010). A lot of literature is available on the use of nanophotocatalyst in the research laboratory for water treatment and air cleaning, but at the commercial level, this is not a perfect approach to minimize the problem. However, heterogeneous nanophotocatalyst recommends fascinating advantages like inexpensive chemicals, additive-free, requires lower concentration to work, and stability. Therefore, heterogeneous nanophotocalysis is a promising approach to achieve at the industrial scale for wastewater treatment.

5. Role of Metal and Metal Oxide Nanomaterials in the Waste Water Remediation

5.1. Iron Oxide Nanomaterials

Iron oxides are found in nature in many different forms. Magnetite (Fe_3O_4), hematite (α-Fe_2O_3) maghemite (Fe_2O_3, γ-Fe_2O_3) are the most common forms of iron oxide (Cornell and Schwertmann 1996). Novel properties and functions of iron oxide nanomaterials (NMs) are widely explored in modern times due to their nano range size, higher surface area to volume ratios, and superparamagnetism (Pan et al. 2010). The low toxicity, chemical inertness, and high biocompatible property of iron oxide nanomaterials (Figure 13) are used in various biotechnology fields, including wastewater treatment (Gupta and Gupta 2005).

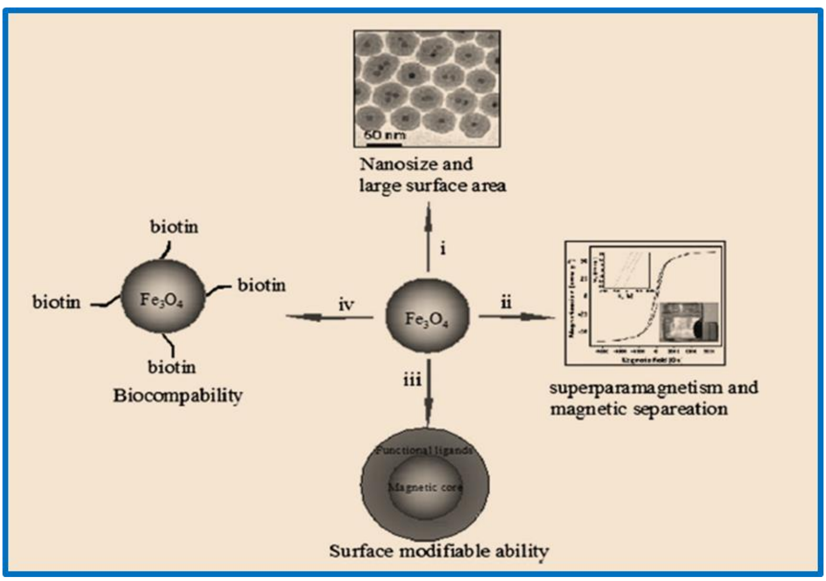


Figure 13. Important properties of iron oxide magnetic nanoparticles for wastewater treatment applications (Reproduced with permission from Piao Xu et al., Copyright©2012, Elsevier).

The unique property of iron oxide nanomaterials is the magnetism that helps in water purification by manipulating the physical properties of contaminants present in the water. Magnetic separation combined with adsorption procedure has been used mostly in water purification technology (Ambashta and Sillanpää 2010). Iron oxide NMs are convenient in wastewater treatment at the industrial level due to their cheap cost, adequate adsorption capacity, easy separation, and enhanced stability (Fan et al. 2012; Carabante et al. 2009).

There are two approaches for the treatment of wastewater using iron oxide NMs:

1. Iron oxide NMs as a nanosorbent or immobilization carrier to enhance removal efficiency; these can be called adsorptive or immobilization technologies.
2. Iron oxide NMs as a photocatalyst to break down contaminants into their less toxic form; they can be called photocatalytic technologies. Literature shows that iron oxide NMs could be used to remove heavy metals like Pb^{2+}, Hg^{2+}, Cd^{2+}, and Cu^{2+} (Ambashta and Sillanpää 2010; Mahdavian and Mirrahimi 2010).

Iron oxide NMs are recently explored for the adsorption of organic contaminant, particularly for water sample treatment in the large volume and quick separation by applying a strong external field. Many experiments have been performed to explore the removal efficiency of organic pollutants by using iron oxide NMs (Luo et al. 2011). Magnetite (Fe_3O_4) hollow nanospheres have been used as adsorbent for removing red dye, and these nanospheres have shown very effective results with a maximum adsorption capacity of 90 mg/g (Iram et al. 2010). The saturation magnetization of nanospheres was 42 emu/g, which was satisfactory for magnetic separation with the magnet. So, magnetic NMs are novel and promising alternatives for organic contaminant adsorption (Ma et al. 2005).

5.2. Zinc Oxide (ZnO) Nanoparticles

Zinc oxide (ZnO) is one of the attractive nanomaterials in recent times as an antibacterial agent. ZnO absorbs UV light and is used in sunscreens, coatings, paints and also plays a vital role in various pharmaceuticals, rubber, and food industries. ZnO is incorporated as an antimicrobial agent into cosmetics (Sonia et al. 2017), surface coatings (Pulit-Prociak et al. 2016), textiles (Cloutier et al. 2015), and cellulose fibers (Varaprasad et al. 2016) to inhibit microbial growth. ZnO is an excellent antibacterial agent due to its outstanding durability, selectivity, and heat resistance property (Padmavathy and Vijayaraghavan 2008). ZnO nanoparticles inhibit microbial growth in three ways, as described in Figure 14:

- Release of ROS
- Release of Zn^{2+}
- Direct contact with the cell membrane

ZnO NPs antimicrobial activity depends on the release of oxygen species from the ZnO surface, which causes fatal damage to microorganisms. Reactive oxygen species induce oxidative stress by damaging their DNA, cell membranes, and cellular proteins. The cell wall damage is done by the surface activity of ZnO, which causes the cell wall, cell membrane decomposition, and leakage of cell contents, which results in cell death (Padmavathy and Vijayaraghavan 2008; Vijayaraghavan 2012;). The release of Zn^{2+}ions is another possible mechanism of ZnO NPs that can damage the cell membrane and its intracellular contents. The antibacterial tests of ZnO NPs in five different media suggested that ZnO NPs toxicity against *Escherichia coli* was shown mainly by the release of Zn^{2+} ions (Li et al. 2008). The same toxicity of ZnO NPs by releasing their Zn^{2+} ions was shown against *Saccharomyces cerevisiae* (Kasemets et al. 2009). One of the possible mechanisms can be the contact between the bacterial cell and NPs, which causes changes in the bacterial cell environment. After contact with ZnO NPs, bacterial cell walls were damaged and disorganized, resulting in the membrane's permeability leads to the internalization of the ZnO NPs (Brayner et al. 2006).

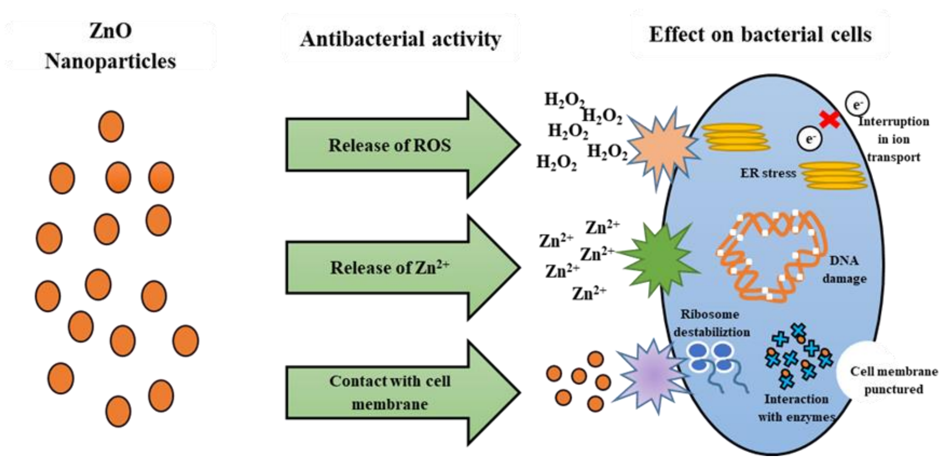


Figure 14. Diagrammatic presentation of ZnO disinfection mechanism.

5.3. Silver Nanoparticles

Silver nanoparticles (AgNPs) have strong antibacterial effects against many microorganisms, including bacteria, viruses, and fungi (Kalhapure et al. 2015; Borrego 2016; Krishnaraj 2012). Due to their higher antimicrobial property, these NPs have been widely used for the disinfection of water. The antimicrobial mechanism of AgNPs is not well understood and various theories rely upon different mechanisms (Figure 15). Some theories describe that AgNPs adhere to the bacterial cell wall and penetrate it, which results in the structural changes of the cell membrane and increase in its permeability (Sondi and Salopek-Sondi 2004). Other theories explain that when the AgNPs interact with the bacterial surface, free radicals generate which in turn, can damage the bacterial cell membrane and cause its death (Danilczuk et al. 2006). One theory suggests that AgNPs can act on the sulfur and phosphorous content found in the DNA and destroy it, which causes the death of cells (Dhanalekshmi and Meena 2016). The normal function of the cell can be disrupted by the interaction of Ag^+ ions with the thiol groups of many essential enzymes, which causes their inactivation (Prabhu and Poulose 2012). In water and wastewater disinfection, AgNPs have been successfully used in recent years. AgNPs are attached to the filter materials for water disinfection due to their antibacterial activity and cost-effectiveness (Quang et al. 2013).

AgNPs on ceramic membranes have drawn awareness due to their disinfection and biofouling reduction for household water treatment (Ren and Smith 2013). It was found that higher porosity in the filters achieves higher bacteria removal compared to those with lower porosity (Kallman et al. 2011). It was also shown that colloidal AgNPs improved the filter performance, and the filter can remove *Escherichia coli* with an efficiency between 97.8-100% (Oyanedel-Craver and Smith 2008). Further studies of AgNPs will reveal their application in waste and wastewater treatment.

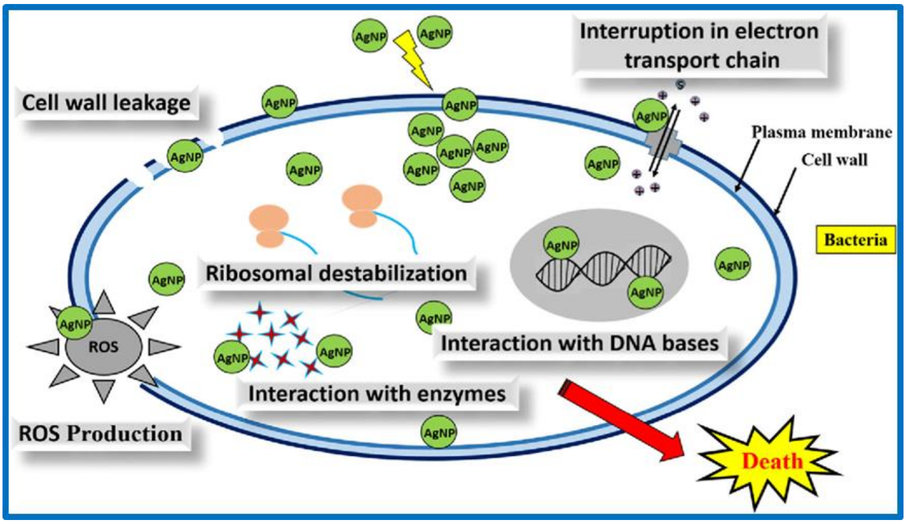


Figure 15. Schematic presentation of antibacterial mechanism activity of silver nanoparticles (Reproduced with permission from Patil *et al.*, Copyright©2017, Springer).

5.4. TiO_2 Nanoparticles

Photocatalytic degradation technology has been successfully used for the removal of contaminants from water and wastewater. In the presence of catalyst and light, these contaminants gradually oxidize into intermediate products with low molecular weight and are finally converted into H_2O, CO_2, and different anions like NO_3^-, PO_4^{3-} and Cl^- (Fujishima and Honda 1972). Common photocatalysts used majorly are metal oxide or sulfide semiconductors. TiO_2 is the most investigated metal oxide in the past years due to its high photocatalytic activity (Figure 16), photostability, reasonable cost, and biological or chemical stability (Guesh et al. 2016; Rawal et al. 2013). The band gap energy of TiO_2 is 3.2 eV, which requires UV light excitation to produce charge separation within the particles. Due to excitation, TiO_2 generates ROS species, which degrades contaminants in short time. Apart from this, TiO_2 NPs are used in the degradation of all types of contaminants such as chlorinated organic compounds, polycyclic aromatic hydrocarbons, dyes, pesticides, cyanide, and other heavy metals (Ohsaka et al. 2008; Guo et al. 2015; Lee et al. 2008; Alalm et al. 2015; Kim et al. 2016; Chen et al. 2016). The photocatalytic activity of TiO_2 NPs is used to kill various bacterial species, viruses, fungi etc. (Foster et al. 2011). According to some studies, the photocatalytic properties of TiO_2 NPs under visible light and UV need some improvement (Anpo et al. 2001). Metal doping improves the absorbance of visible light of

TiO_2 NPs to increase their photocatalytic activity under UV irradiation (Mu et al. 1989). Silver (Ag) is a good candidate as a dopant of TiO_2 NPs because it enables the visible light excitation of TiO_2 NPs and improves the photocatalytic inactivation of viruses and bacteria (Seery et al. 2007; Page et al. 2007; Kim et al. 2006).

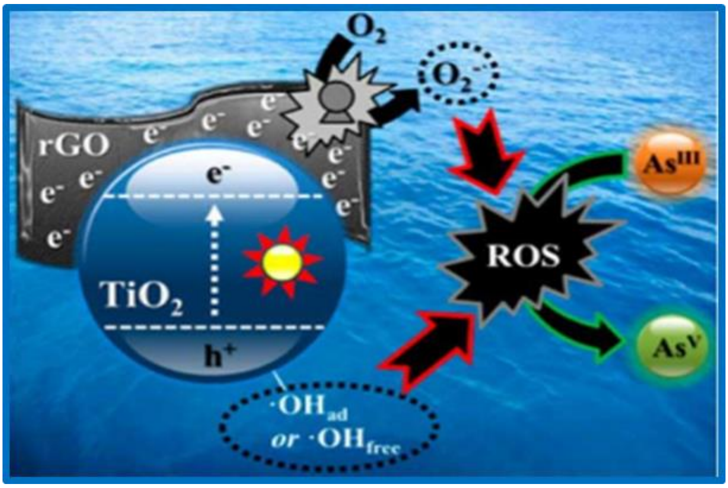


Figure 16. Schematic presentation of the mechanism of TiO_2 photocatalytic process. (Reproduced with permission from Haijiao Lu et al. Copyright©2016, Hindawi).

The difficulty in the case of TiO_2 NPs to treat wastewater is their recovery, mainly when they are used in the suspension. Photocatalysis of TiO_2 NPs with membrane technology has attracted much attention for overcoming the TiO_2 NPs recovery problem. Several membranes have been used with TiO_2 NPs, such as polymethyl methacrylate, poly (vinylidene fluoride), polyethersulfone, and poly (amide-imide) (Hamming et al. 2009; Wang et al. 2013; Razmjou et al. 2011; Rajesh et al. 2013). N, N′-methylene-bisacrylamide used as the cross-linker and ammonium persulphate as the initiator pair for the acrylamide polymerization in aqueous solution for the synthesis of TiO_2/poly[acrylamide-co-(acrylic acid)] composite hydrogel. Separation of TiO_2 NPs can be easily done through simple filtration using polymeric membranes (Kangwansupamonkon et al. 2010).

5.5. Carbon Based Nanomaterials

Carbon-based nanomaterials are majorly categorized based on their geometrical structures. Carbon nanostructure particles have different shapes, namely tube-shaped, horn-shaped, spherical, or ellipsoidal. Nanoparticles having tube-like shapes are called carbon nanotubes; spheres or ellipsoids belong to the set of fullerenes, and horn-shaped particles are called nanohorns (Das et al. 2014). These carbon-based nanomaterials have been generally used in nano-electronics, production matter of conductive plastics, gas storage, displays, textiles, antifouling paints, batteries, gas biosensors etc. (Ramnani et al. 2016).

5.5.1. Fullerenes

Fullerene is the allotrope of carbon discovered by Kroto et al. (1985), for which they were awarded the Noble prize for chemistry in 1996. The fullerene family consists of atomic carbon clusters (n > 20) constituents in the spherical form. One of the best examples of fullerenes is C_{60}, also called Buckminster fullerenes (Lam et al. 2006). Fullerenes show various geometries, such as nanotubes and spherical cages (C_{60}), and are used in wastewater application research. The C_{60} fullerene has very low solubility in the water. To overcome this problem, they are modified on surface clustered (nC_{60}) or mixed with surfactant or stabilization agent to reach the water. C_{60} is a potent photocatalyst used in wastewater treatment, in UV and solar disinfection reactors etc. It enhances the oxidative process that can destroy various contaminants that include carcinogens, endocrine disruptors and is also helpful in water disinfection (Tsydenova et al. 2015).

5.5.2. Carbon Nanotubes (CNTs)

Carbon nanomaterials have unique structures and electronic properties due to which these materials are fascinating and attractive for fundamental studies and various applications. They are used for water and wastewater treatment due to:

1. Extraordinary capability to adsorb a broad range of contaminants,
2. Speedy kinetics,
3. Specific surface area, and
4. Excellent selectivity towards aromatics (Khin et al. 2012).

Carbon nanomaterials have several forms, carbon beads, carbon fibers, carbon nanotubes (CNTs), and nanoporous carbon (Khin et al. 2012). Among these, CNTs have gained the most attention in recent years. CNTs are graphene sheets rolled up in cylindrical form and having a diameter range of <1 nm (Chatterjee and Deopura 2002). CNTs possess excellent adsorption capabilities due to higher surface area and larger porous structure for many contaminants such as ethylbenzene, dichlorobenzene, Pb^{2+}, Zn^{2+}, Cd^{2+}, and Cu^{2+} and dyes (Lu et al. 2008; Peng et al. 2003; Li et al. 2003; Madrakian et al. 2011). CNTs are classified into two types (Figure 17).

Multiwalled carbon nanotubes (MWCNTs) have multiple layers of concentric cylinders with the spacing of about 0.34 nm between adjacent layers**.** Whereas, single-walled carbon nanotubes (SWCNTs) have a single layer of graphene sheet in the cylindrical tube form (Zhao and Stoddart 2009).

Both MWCNTs and SWCNTs are used for the removal of contaminants in the water. CNTs are often combined with other metals which improves their adsorptive, optical, mechanical, and electrical properties (Ray and Shipley 2015). The functionalization increases nitrogen, oxygen, or other group numbers on CNTs surface which increases their dispersibility and improves specific surface area (Adeleye et al. 2016). Gupta et al. (2011) reported the CNTs as a support for magnetic iron oxide. Using CNTs adsorption qualities and iron oxide magnetic properties, a “composite” adsorbent is prepared, which is used to remove toxic hexavalent chromium ions from water (Chatterjee and Deopura 2002). Table 3 showed the organic pollutants removal by various types of carbon nanotubes.

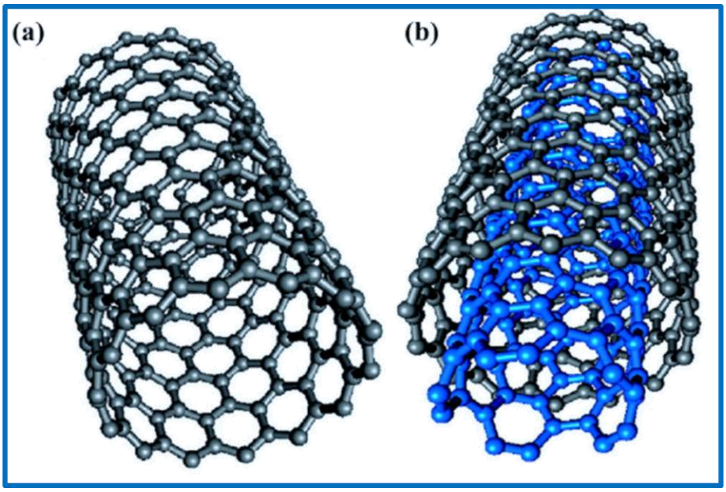


Figure 17. Structure representation of SWCNTs and MWCNTs respectively (Reproduced with permission from Chella Santhosh et al., Copyright©2016, Elsevier).

Table 3. Removal of organic pollutants using various types of carbon nanotubes

S.No.	Types of CNTs	Organic pollutants	References
1.	MWCNTs	Methylene Blue, olaquinodox, Tetracycline, Methyl orange	Wang et al. 2012; Zhang et al. 2011; Álvarez-Torrellas et al. 2016; Zhao et al. 2013
2.	Alkali activated MWCNTs	Methylene Blue	Ma et al. 2012
3.	KOH activated MWCNTs	Toluene, ethyl benzene	Lou et al. 2011
4.	Calcium alginate/Chitosan/ Fe_2O_3SWCNTs	Methyl orange	Zhu et al. 2010
5.	SWCNTs	4-chloro-2-nitrophenol	Mehrizad et al. 2012
6.	Oxidized SWCNTs	Basic red 46 (BR 46)	Moradi 2013
7.	Others SWCNTs and MWCNTs	Oxytetracycline, Ciprofloxacin, Norfloxacin	Ncibi and Sillanpää 2015; Yang et al. 2012

5.5.3. Graphene Nanoparticles

Another allotrope of carbon, graphene, is also a promising nanomaterial under the research for wastewater treatment. Due to the unique properties of graphene and graphene-based materials, these are used for environmental remediation and help in the new potentialities to improve different environmental processes. Graphene and graphene-based nanoparticles shown in Figure 18 serve as efficient adsorbents due to their bigger surface area and electron-rich environment. Graphene oxide (GO) is a potential adsorbent for metal ions due to the presence of a strong functional group on the graphene oxide surface. Many studies have reported graphene-based materials as adsorbents for the removal of inorganic pollutants from the water (Zhao et al. 2011). In most studies, GO was employed as a model adsorbent to remediate inorganic metal ions in the water. GO composite with metal oxide has been used as more effective adsorbent for the removal of various pollutants (Wu et al. 2013; Zhao et al. 2011). Flower-shaped TiO_2 on GO hybrid (GO-TiO_2) has been used to remove Zn^{2+}, Cd^{2+}, and Pb^{2+} ions from the water (Lee and Yang 2012).

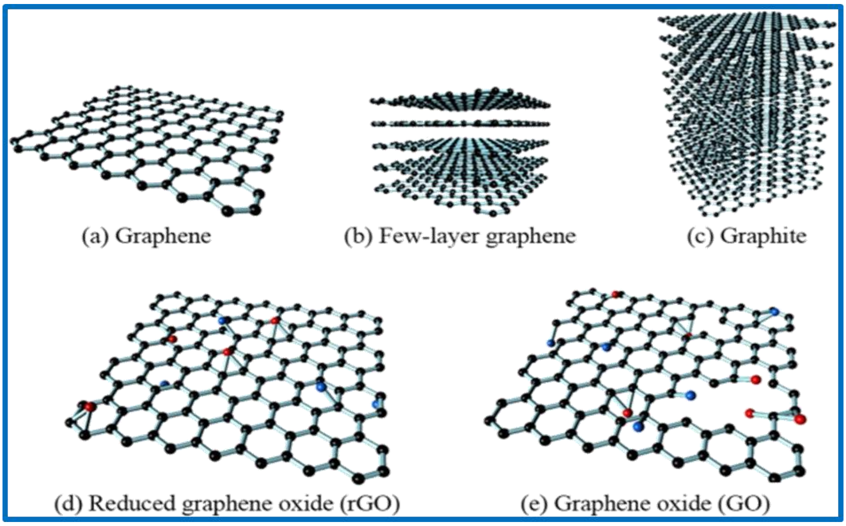


Figure 18. Graphene family nanomaterials (Reproduced with permission from Siaw Fui Kiew et al., Copyright©2016, Elsevier).

Graphene based adsorbents have also been found to be very effective for the removal of various organic pollutants from water and Table 4 summarizes the removal of some of the inorganic and organic pollutants using graphene based nanocomposites.

Table 4. Graphene based nanocomposites for the removal of inorganic and organic pollutants

S. No.	Graphene Nanocomposite	Inorganic/organic pollutants	References
1.	MnO_2-GNs	Hg (II)	Sreeprasad et al. 2011
2.	TiO_2-GO	Pb (II), Methyl orange (MO)	Madadrang et al. 2012; Pastrana-Martinez et al. 2012
3.	Graphene nanosheets (GNs)	Pb (II), Methylene Blue (MB)	Huang et al. 2011; Liu et al. 2012
4.	Graphene oxide (GO)	Pb (II), MB, Tetracycline, Doxycycline	Lee and Yang 2012; Gao et al. 2012
5.	GO-Fe_3O_4	Cu (II), MB, Neutral Red	Hur et al. 2015; Xie et al. 2012
6.	SiO_2-GNs	Pb (II)	Hao et al. 2012
7.	GO-silica-Fe_3O_4	Pb (II), Cd (II)	Wang et al. 2013
8.	GO-EDTA	Pb (II)	Madadrang et al. 2012
9.	GO-$MnFe_2O_4$	Pb (II)	Kumar et al. 2014
10.	Fe_3O_4-GNs	MB, Congo red	Yao et al. 2012

6. Patented Products of Nanomaterials for Wastewater Treatment

Various patented products of nanomaterials that are used for the wastewater treatment are described in Table 5.

Table 5. List of patented products of nanomaterials for purification and treatment of waste water

S. No	Patent name	Patent No.	Activity of Nanomaterials	Inventers details	Patent Publication Date	References
1.	Process for biochemical treatment of waste water using nano materials	US 20030010712A1	Carbon black used as a nanomaterial to induce micropores for the degradation of organic pollutants in the waste water	Gao et al.	16 January, 2003	Gao et al. 2003
2.	Magnetic nanoparticles decorated activated carbon nanocomposites for purification of water	US 20160243523A1	Magnetic nanoparticles decorated activated carbon nano-composites display both magnetic and adsorbent characteristics and used for the purification of water	Saini et al.	25 August, 2016	Saini et al. 2016
3.	Drinking water filtration device	US 007390343B2	Device contain Nano alumina fibers used for the purification of water.	Tepper and Kaledin	24 June, 2008	Tepper and Kaledin 2008
4.	Water treatment by dendrimer enhanced filtration	US 007470369B2	Dendritic macromolecules (cation binding, anion binding, organic compound binding etc.) binds to contaminants, and filtered the water	Diallo	30 December, 2008	Diallo 2008
5.	Adsorption filter	US 20060123991A1	Adsorption filter contain activated carbon particles for the purification of water	Braeunling et al.	15 June, 2006	Braeunling et al. 2006
6.	Reduced graphene oxide-based composites for the purification of water	US 20130240439A1	A nanocomposite is disclosed comprising reduced graphene oxide (RGO) act as an adsorbent comprising the nanocomposite bound to silica by using chitosan	Pradeep et al.	19 September, 2013	Pradeep et al. 2013
7.	Double chamber water purification device	US 008425771B2	A portable device for filtering and purifying water that uses activate carbon or nano-filters	O'Brien and Engel	23 April, 2013	O'Brien and Engel 2013
8.	Nanomesh method for purification of fluids	US 007419601B2	Carbon nanotubes used for the removal of contaminants from a fluid	Cooper et al.	2 September, 2008	Cooper et al. 2008
9.	Separation system and efficient capture of contaminants using magnetic nanoparticles	US 007699979B2	Magnetic nanoparticles are used to capture and separate the contaminants	Li et al.	20 April, 2010	Li et al. 2010
10.	Waste water purification with nanoparticle treated bed	US 008226830B2	Nanoparticle treated particle packs such as sand beds used as effective filter for the purification of waste water	Huang and Crews	24 July, 2012	Huang and Crews 2012
11.	Photocatalytic metal oxide nanomaterials use for organic waste decontamination in water	WO 2013085469A1	Black TiO_2 nanoparticles serves as photocatalysts for the decomposition of pollutant organic compounds in the water	Chen and Richuan	13 June, 2013	Chen and Richuan 2013

Conclusion and Future Perspectives

There is an essential need for high-level water technologies to ensure excellent water quality, eliminate biological and chemical pollutants and enhance wastewater purification at the industrial level in the current situation. Water is elixir of life for all the living creatures found on the earth. Polluted or contaminated water is one of the significant challenges of the modern era and several reasons are responsible for water contamination. The contaminated water contains undesirable substances such as microorganisms, harmful chemicals which render it unsafe for all purposes. Untreated polluted water poses a significant threat to living organisms and to the environment. It is therefore crucial to develop a planned strategy for the detection of the pollutants and their nullification from various water bodies. Nanotechnology is an ideal and promising way to enhance water monitoring techniques and their treatment processes. Several nanomaterials have been developed and explored successfully for wastewater treatment. Nanotechnology has a significant prospective in magnifying water quality by wastewater management due to its cost-effectiveness and high ability to expel and recuperate the pollutants. The anti-pollutant properties of nanomaterials are due to their nano-range size, the larger surface to volume ratio, high reactivity, and high adsorption responsible for removing the water contaminants. Further research is required to develop cost-effective methods to synthesize nanomaterials and test nanomaterials efficiency at the industry scale to apply for wastewater purification. New potential sensing strategies including, DNA nanosensors can be a major revolution in the field of scientific and technological development of environmental monitoring. To date, few kinds of nanomaterials have gained much interest commercially. Cost-effectiveness is crucial to ensure their broad level applications in wastewater treatment. Next-generation research should be devoted to enhance the industrial efficiency of nanomaterials. Besides, with the development of excellent nanomaterials for their applications in wastewater treatment, there comes increasing concerns about their potential toxicity to human health and the environment. In the literature, several nanomaterials have been reported for their harmful effects on the environment and human health. However, standards for measuring nanomaterials toxicity are generally inadequate at present. Thus, complete exploration of nanomaterials’ toxicity is in vital need to ensure their actual applications. Further development is needed to compare the performances of different nanomaterials and select promising nanomaterials. Consequently, the evaluation of the nanomaterials performance in wastewater treatment should be perfected in the future time.

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Chapter 11

MOBILE PHONE DESIGN WITH EXTENDED PRODUCER RESPONSIBILITY APPROACH

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ABSTRACT

Background

The increasing demand and use of electronic devices caused a very high and uncontrollable amount of WEEE (Waste Electrical and Electronic Equipment). One of the many devices with huge amount of waste was mobile phone. The main factors causing such problem included: producer's irresponsibility towards products' end-of-life phase, a high level on mobile phone dismantling difficulty, and a low level of user awareness. The aim of this study was to design a mobile phone with low level dismantling difficulty, along with educating users about the importance of processing mobile phone waste, with EPR (Extended Producer Responsibility) approach.

Methods

During the design process, researcher conducted a variety of literature studies, observations, interviews, and surveys towards professionals, users, and mobile phone repairmen. The method that was used for this study was design cycle, this was done to ensure the direction and objective of the research remain clear throughout the design process.

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Results

The output of this research is a 3D printed mobile phone prototype that can be dismantled by both professional and non-professional users. The development in architectural design inside the mobile phone resulting in component integration that does not need the presence of adhesive substance. For all the connection occurred on the logic board are using pogo pin. Users can send the mobile phone back to the producer after the disassembly process has been done.

Conclusion

Easy-to-dismantle mobile phone, along with user involvement in sending it back to the producer succeeds on solving the problem of uncontrolled WEEE, along with raising users' awareness towards recycling their unused mobile phones.

Keywords: EPR, WEEE, mobile phone, disassembly process, recycle

1. INTRODUCTION

With the increasing demand on electronic devices, along with human lifestyle that is very dependent on gadgets, the number of WEEE (Waste Electrical and Electronic Equipment) that follow also continue to rise (Khan, Inamuddin, and Asiri 2020). As we all know, without the presence of modern electronic devices, we as human will struggle to accomplish our daily task. Many aspects of human's life, such as transportation, education, communication, infrastructure to health, they all need to operate using modern technology devices to meet human needs. As a result, each one of us has at least one electronic device, while many of us have more than one. Those high demand and needs are causing high number of production and sales.

Along with countless number of ownerships, come a great number of wastes. One of the many devices with a huge number of wastes is mobile phone. In 2017, mobile phone users in Indonesia has reached 194 million, and is expected to reach 220 million users by 2025 (GSMA 2018). Mobile phone is a very complex and integrated device that need a special treatment to get it recycled safely and without polluting the environment. This electronic device contained a very complex structure and component that are each integrated into one part. Even worse, the building materials themselves are very toxic and should never have direct contact with the environment in a long period of time.

In the meantime, the recycling facility in Indonesia is still lacking and cannot contain such a huge number of wastes. Most of the wastes were dumped on the landfill (Ministry of Environment Republic of Indonesia 2013), or being incinerated illegally by unauthorized party. Just a little amount of that wastes that were properly treated or being recycled. As mentioned in the previous section, all those electronic wastes contained toxic and dangerous substances that can potentially harm the environment and all living organisms in it. They can pollute the soil, that goes into the water, and evaporate into the air, which if we think about it, human will also get the impact sooner than later. Globally, only 10% of mobile phone wastes were recycled (Welfens, Nordmann, and Seibt 2016). In 2011, Nokia conducted a survey to get the number of mobile phones that were being recycled around the world, and the result in Indonesia was only at 1% (Tanskanen 2012). The level of mobile phone waste recycling in Indonesia is directly proportional with the low level of awareness about the problem in question.

The producer of mobile phone also takes role in that situation. In designing a product, the lifecycle of itmust be considered right from the moment of the production begins until the end-of-life phase of the product itself. That includes the design process, production, distribution, up to the end of product's life that must be returned to the producer. This system we called EPR (Extended Producer Responsibility) ensure the product to be easy to produce, maintain, and recycle. In product design wise, mobile phone can and should be improved by using EPR approach, which will be executed in this research. Mobile phone design that is difficult to disassemble has a huge impact in the reusing and recycling process, particularly in the component separation process. With the right design, mobile phone can also increase user awareness, in which also something that still lacks in our society. Increasing awareness can be done by using an interactive design, both in the product and packaging. If the system is being executed properly, this can educate as well as raising awareness about the importance of recycling unused phone.

In short, the aim of this research is:

- To design a mobile phone concept with EPR (Extended Producer Responsibility) approach: easy to be disassembled to make it easy to be recycled
- To create a processing and management system as one aspect of EPR system
- To educate the users through the system that is implied on the mobile phone design
- To involve users in controlling the life cycle of the mobile phone to ensure that the product will return to the producer.

The problem limitation in this research is:

- Product design is focused on the lock mechanism/system in between each component with the aim for it to be easy to disassemble. This research is not focusing on the technology or mobile phone features, such as operating system, application development, phone accessibility, UI/UX etc.
- The designing of controlled mobile phone life cycle is only until it is returned to the hand of the producer, with the presumption that the producer has already had a recycling facility and system for the wastes.
- This mobile phone design concept is not intended to replace any mobile phone brand design.
- The study and designing process on this research only covers a general mobile phone design. This exclude mobile phones with exclusive features, such as foldable smart phone, etc.

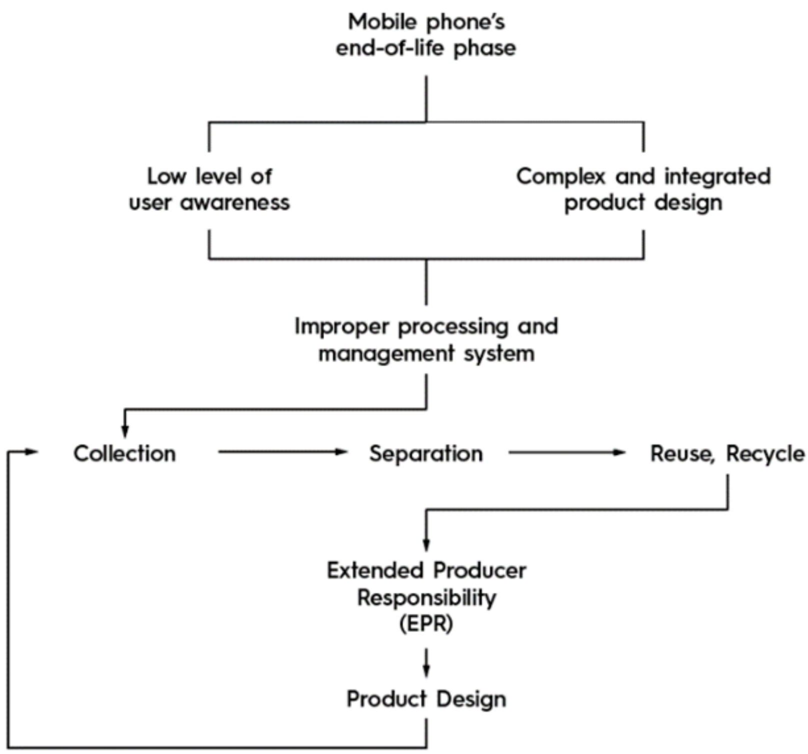


Figure 1. Framework.

In this research, we used this framework below to help the process to stay inside the scope of problem, but still able to reach the solution of the raised problem. The flow of the chart has been adjusted to match with the result of research and studies and the observation that has been done.

2. METHOD

In this study, 'Design Cycle' method was applied to ensure the direction and objective of the research remain clear throughout the design process. This following method ensure the design process starting from problem definition, continued to research and study, analysis and troubleshooting, until the final concept is made and can be tested to solve the defined problem. The big picture of the method can be seen in Figure 2 below.

The first step in this research was to explore the existing problems, which was the uncontrolled amount of WEEE due to producers' responsibilities (EPR related issues) and lack of users' awareness. After the core of the issue was understood, we started to do research and conduct study of literature. To understand the existing problems, we conduct a research and study process about Waste Electrical and Electronic Equipment (WEEE), Mobile Phones, and Extended Producer Responsibility (EPR). The following step would be to analyse and build a solution according to the results of the previous step. This way, we can build a new concept of product that apply EPR approach in the form of design alternatives, which supposedly can be a new way of designing a mobile phone. Finally, a prototype will be tested out to see whether it succeed or not on being a solution for the problem we mentioned before.

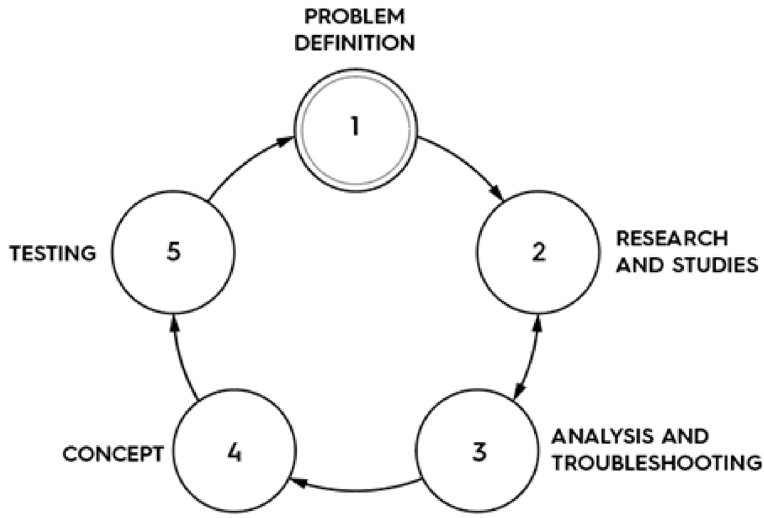


Figure 2. Design Cycle Method.

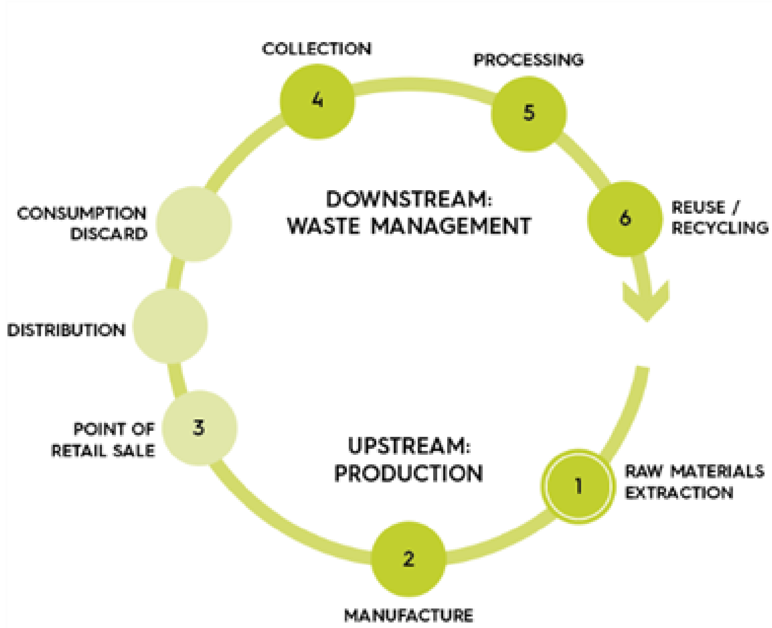
3. RESULT

3.1. Extended Producer Responsibility

EPR which stands for Extended Producer Responsibility is also known as producer takeback. This system or regulation oblige all producers to fund and manage their products that has already been in end of life phase (Huang, Atasu, and Beril Toktay 2019). When a producer applies this system in their production process, they will ("Extended Producer Responsibility" 2001):

- Use an eco-friendly material;
- Not exploit a material;
- Design a product to have a longer lifespan and have more purpose;
- Maintain the waste treatment cost as low as possible;
- No longer divert the waste treatment cost to the government or taxpayers.

By seeing the lifecycle above, we know that a new concept of mobile phone lifecycle design needs to be applied. From the overall studies and analysis that were done, the application of EPR system in this research would be something like this:



Source: Extended Producer Responsibility, 2001.

Figure 3. EPR Cycle.

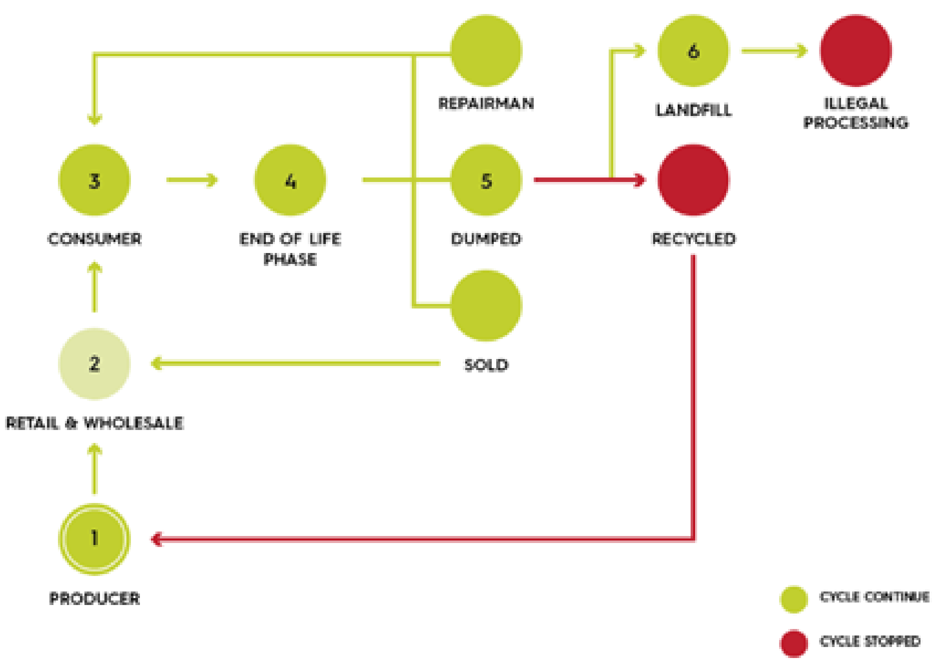


Figure 4. Mobile Phone Linear Lifecycle.

Table 1. EPR Application on Research

No.	EPR System Aspect	Application in Research
1.	Upstream and Downstream cycle (closed loop)	Transformation on mobile phone linear lifecycle into circular cycle. This phase will include users on sending the product back to the producer
2.	Product design with a longer lifespan; Maintaining low waste management cost	Designing a mobile phone that can be disassembled easily by users. Interactive design on both product and packaging ensure the ease of the process to send back the disassembled product back to the producer
3.	Use safe and eco-friendly materials	The use of reusable and recyclable material that cause no harm to the environment

3.2. Mobile Phone Component

Totalling 17% of the amount of WEEE, mobile phone waste was very hard to be processed (Sivaramanan 2013), whether to be reused or recycled. This was due to the integrated and complex architectural design of mobile phone. Only 1% (Tanskanen 2012) of the total amount was successfully recycled, and the rest was just being piled up on the landfill polluting the environment. In general, mobile phone composed of four main parts:

Table 2. Mobile Phone Hazardous Content

No.	Component	Substance	
		Hazardous	Non-Hazardous
1.	Display	Lead (Pb) = Toxic/poison Mercury = Toxic/poison Liquid Crystal = Corrosive	Glass, plastic = PMMA, PET Metal = Steel, aluminium
2.	Logic Board	Lead (Pb) = Toxic/poison Mercury = Toxic/poison BFRs (Brominated Fire Retardant) = Toxic/poison	Copper, iron, tin (Sn), nickel, zinc (Zn), silver, gold, palladium
3.	Battery	Electrolyte solution = Flammable and corrosive	Aluminium, nickel, manganese, cobalt, cadmium
4.	Housing	-	Plastic = PET, HDPE Metal = Aluminium, stainless steel
Note:		Most of the lead (pb) found in display (LCD) are from the solder (37-40% = 8.5 gr per display). The substitute for lead solder is silver (Ag), copper (Cu), or bismuth (Bi)	

- Display (Ylä-mella, Pongrácz, and Keiski 2014)
  - a. 49% plastic, 38% glass, 8% metal, 4% PCBs, 1% indium tin-oxide, liquid crystals, dan adhesive substances
    - – Plastic: PMMA (Polymethyl Methacrylate), PET (Polyethylene Terephthalate) and PC (Polycarbonate)
    - – Metal: Steel and Aluminium.
- Logic Board/PCB (Printed Circuit Board)(Sohaili, Muniyandi, and Mohamad 2012)
  - b. 30% metal, 70% substrate: thermoset resins and other substances (plastic, ceramic, adhesive, etc.)
    - – Metal: Copper (Cu), iron (Fe), tin (Sn), zinc (Zn), silver (Ag), gold (Au), palladium (Pd)
    - – Nickel was used as ananti-corrosive coating.

- Battery – Lithium Ion
- Housing – Aluminium, stainless steel, plastic (PET and HDPE).

3.3. Interview and Observation

The first interview and observation conducted was in E-centre Supermall Karawaci. These were done gradually from October 2019 to November 2019 toward five different unauthorized mobile phone repair counters (Junianto and Sugandha 2019).

Table 3. Observation on Mobile Phone Service Centre

No.	Observation	Result	Picture
1.	Friday, October 18, 2019 - E-centre Supermall Karawaci Christine Phone Cell	Unused mobile phone parts/components will be used for personal experiment Outdated parts will be thrown away in a dumpster No specific buyer for the unused parts No waste management system in this counter	
2.	Friday, October 26, 2019 - E-centre Supermall Karawaci CintaKarya Cellular	Reusable mobile phone parts/components will be reused, the unused parts will be thrown away in a dumpster No specific buyer for the unused parts No waste management system in this counter Mobile phone distributors do not care about the waste of their mobile phone	
3.	Friday, October 26, 2019 - E-centre Supermall Karawaci Permata Service	Reusable mobile phone parts/components will be kept and stored Unused parts will be placed as a store display, or thrown away The most amount of waste is from unused display and battery There is someone/institution who will buy unused parts	
4.	Wednesday, November 6, 2019 - E-centre Supermall Karawaci Bagas Cellular	No waste management system in this counter No special disposal for unused mobile phone parts/components Unused parts will be placed as a store display, or thrown away Reusable parts will be kept and used for another mobile phone that needed to be repaired	
5.	Wednesday, November 6, 2019 - E-centre Supermall Karawaci King Service	Unused mobile phone parts/components will be immediately thrown away No specific buyer for the unused parts No waste management system in this counter The owner does not feel that management system is necessary, because everything seems just fine the way it is now	

None of the service places that were observed has a processing and management system for the waste of unused mobile phone parts/components. Further observation was done to collect data about the disassembling process of the mobile phone itself. From this observation, it can be concluded that disassembling mobile phone was a very tricky and long process, and the users must be a professional to do it without breaking the phone. A survey of mobile phone users about their lifestyle and behaviour was done. We got 72 responds that stated:

Table 4. Analysis on Mobile Phone Disassembly Process

Variable	Battery	Display	Logic Board	Housing	Score
Mobile Phone ‘A’ 	5	2	3	1	2,75
Mobile Phone ‘B’ 	5	5	5	4	4,75
Mobile Phone ‘C’ 	1	4	4	3	3

- 70.8% users own one mobile phone, and the rest own more than two mobile phones
- 65.3% users own more than one unused mobile phones; that mostly was still working
- 63.9% of that unused mobile phones were just stored and not being treated as how mobile phone wastes should be treated
- No respondent had ever recycled their mobile phone, and 45.8% of them did not know that mobile phone could be recycled
- 72.2% users had never tried to dismantle mobile phone
- 77.3% users that had ever done it said that the difficulty level was 3-5 (1 = easy, 5 = difficult)
- 57% users said that the hardest component to be disassembled was logic board and display.

For one of the key aspects from EPR system is the ease of disassembling process, a trial and further research on this area need to be explored. From Table 5 we can see that these three different mobile phones had different scores. Each of the components were given a score from 1 (easy) to 5 (difficult). Overall, the easiest one to be disassembled would be ‘Mobile Phone A’ with the lowest score of 2,75; and the most difficult one would be ‘Mobile Phone B’ with the highest score of 4,75.

3.4. Proposed Solution

To solve the problems of uncontrolled WEEE, lack of user awareness, producer's irresponsibility; the following solution were proposed:

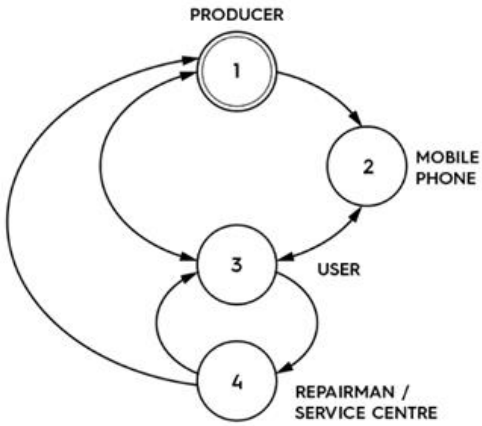


Figure 5. Designed Cycle for Proposed Solution.

Table 5. Proposed Solution

No.	Problem	Proposed Solution
1.	Highly integrated and complex architectural design, very difficult to be dismantled	Designing a mobile phone that is easy to dismantle, using a various lock system Avoiding the use of adhesive
2.	Containing hazardous substances/material	Substitute or minimize hazardous material
3.	Lack of user awareness	Designing a product that can directly/indirectly educate the user about the importance of recycling mobile phone waste
4.	User behaviour that does not support and participate in waste management cycle	Encourage the user to be a part of the cycle by sending the disassembled phone back to the producer
5.	Illegal WEEE processing	Application of closed loop system to make sure that the lifecycle of the product remains controlled

3.5. Product Structure

3.5.1. Mobile Phone Basic Structure

The basic structure for our designed mobile phone consists of display, housing, PCB/logic board, and battery. The part that will be retained is the one that has important roles and/or the main structure of a mobile phone that cannot be reduced nor eliminated. Otherwise, the part that can be reduced or eliminated will not be used in our mobile phone architectural design to minimize the use of parts and materials.

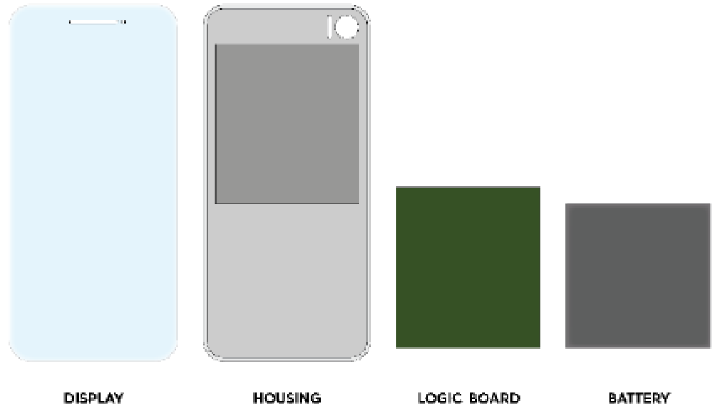


Figure 6. Designed Mobile Phone Basic Structure.

3.5.2. Mobile Phone Quantified Structure

In designed quantified structure 'A,' logic board will be put on the upper half of the phone, and the lower half will be used for battery placement. Both are inside a unibody housing with the display on top acts as a closing lid. The logic board placement on the upper part means that all the components will also be put on the upper side, since all of them must be connected directly to the logic board (we do not want to use flat cable to minimize the use of parts and materials). The components which are usually at the bottom, such as speaker, charging port, etc. will be moved to the top part or will be eliminated.

In designed quantified structure 'B,' logic board will be put on the bottom half of the phone, and the upper half will be used for battery placement. Just like the quantified structure 'A,' both are inside a unibody housing with the display on top acting as a closing lid. Logic board placement on the lower half of the phone means that all the components inside will also be put on the lower part of the phone. The components that are usually put on the upper half such as, earpiece speaker, camera, etc. will be moved to the bottom or eliminated.

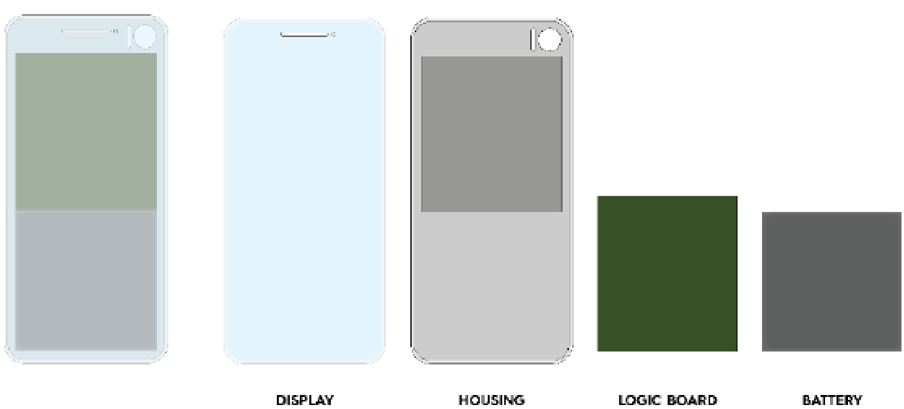


Figure 7. Designed Mobile Phone Quantified Structure 'A.'

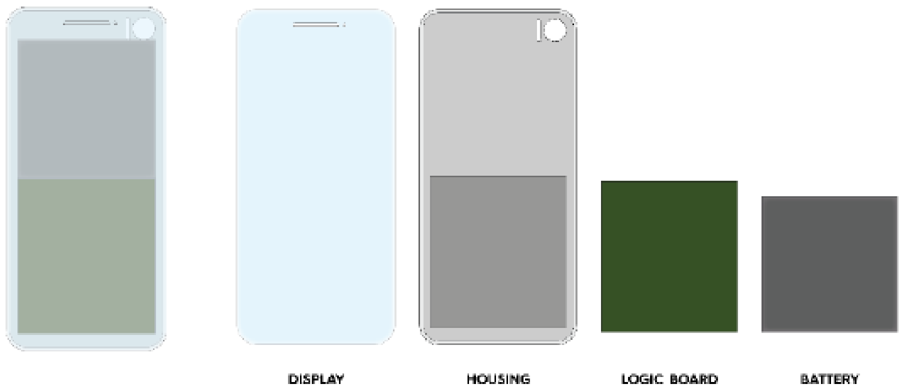


Figure 8. Designed Mobile Phone Quantified Structure 'B.'

In designed quantified structure 'C,' the logic board will be shaped like a mirrored C alphabet, with the gap in the middle for battery placement. Just like the previous designed structures, both the logic board and the battery will be put inside a unibody housing with the display acts as a closing lid. With this kind design, all the needed components inside the phone can be placed either on the top half or the bottom half of the phone, which makes this design more versatile.

In designed quantified structure 'D,' the logic board will be shaped like a C alphabet, with the gap in the middle for battery placement. Just like the previous designed structures, both the logic board and the battery will be put inside a unibody housing with the display acts as a closing lid. With this kind design, all the needed components inside the phone can be placed either on the top half or the bottom half of the phone, which makes this design more versatile.

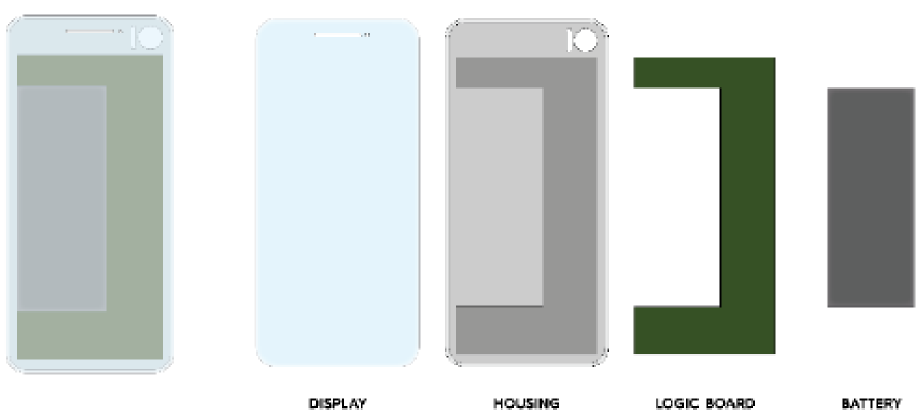


Figure 9. Designed Mobile Phone Quantified Structure 'C.'

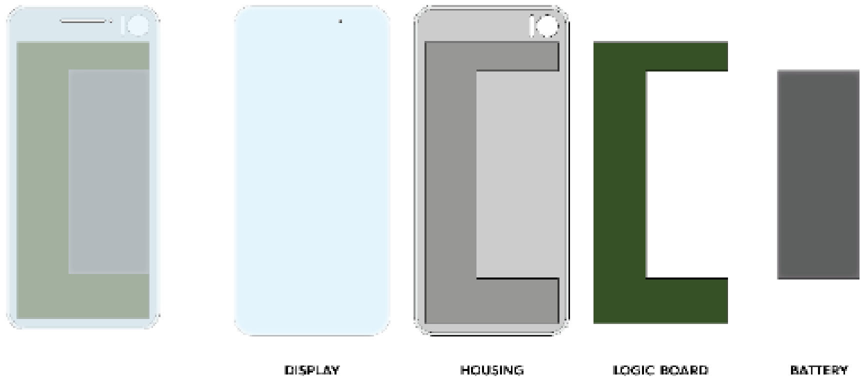


Figure 10. DesignedMobile Phone Quantified Structure 'D.'

Table 6. Advantages and Deficiency on each Quantified Structures

QS	+	-
A	Square shaped logic board is more durable in the dismantling process. Phone's components are more common, and some must be placed on the upper half of the phone, such as camera, earpiece speaker, and power button.	Components rearrangement is needed to make the bottom half of the phone empty.
B	Square shaped logic board is more durable in the dismantling process.	Components rearrangement is needed to make the bottom half of the phone empty. Focusing all the components to be in the bottom part of the phone is more difficult, as some part must be on the upper part, such as camera, earpiece speaker, and power button.
C	Components rearrangement is not needed, considering the mirrored 'C' shaped logic board will cover most of the part inside the phone.	Mirrored 'C' shaped logic board is more fragile and is easier to get stuck with other components in while being pulled out in the dismantling process.
D	Components rearrangement is not needed, considering the 'C' shaped logic board will cover most of the part inside the phone.	'C' shaped logic board is more fragile and is easier to get stuck with other components in while being pulled out in the dismantling process

3.6. Dummy

In this process, various dummies were made to see which architectural design was the most fit to our proposed solution. These 5 dummies were tested on eight users to get a valid feedback from their perspective. The process was using iterative method, in which each dummy will be reviewed and revised according to feedback, and made into the second dummy, and so on. From that user review, we obtained a data that conclude dummy no. 5 to be the most fit for our proposed solution.

3.7. Prototype - Design Alternative

After conducting specific survey about users' preferences on mobile phone industrial design, we managed to get a respond from 103 users. From that process, we can combine the chosen architectural design from the selected dummy with physical design from users' preferences into what we called design alternative.

Each alternative will be tested using Iterative Method to get each design improved. After doing QFD (Quality Function Deployment) on three alternative designs, design alternative 3 was chosen to be made into final design, hence making the prototype.

Table 7. Dummy

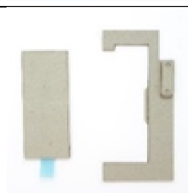
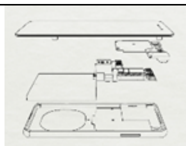
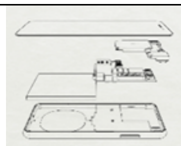
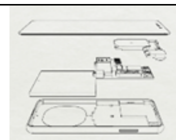
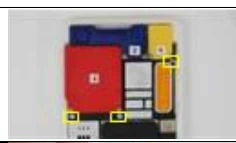
Mock-up	Picture		
	Pre - Disassembled	Post - Disassembled	Detail
1			
2			
3			
4			
5			

Table 8. Design Alternative

	Design Alternative		
	1	2	3
Sketch	 	 	 
Prototype	 	 	 
Analysis	Some of the components need to be resized (screw hole, lock on display)	Some of the components need to be resized (screw hole, lock on display, pogo pin connector) Charging coil spaceneed to be printed	The display needs to be resized in width by 0,2 mm

3.8. Prototype - Final Design

Table 9. Final Design

Final Design					
1		Packaging	6		Screwdriver to hold the display and housing together
2		Screwdriver is included	7		All components are connected to logic board with screws
3		Manual instruction on 'How to Use this Phone' and 'How to Send this Phone Back"	8		All components can be lifted by finger after being unscrewed
4		Tray to hold small parts/components	9		All components are using pogo pins connector to logic board
5		Battery Tray	10		Each component has its own place in the bottom container of the packaging

The output of this research was an easy-to-dismantle mobile phone along with the interactive and intuitive packaging. The goal was not only to make the phone easy to be recycled, but also to educate the user using EPR approach applied design. The first time the user opened the packaging, they will have to attach the battery for the mobile phone to be working. This was an introduction phase, by doing this step the user would learn on how to disassemble the display from the housing. With this learning phase, user is expected to understand the disassembling process, so they can send their phone back to the producer with no difficulty.

3.8.1. Product Specification

Figure 11. Product Specification.

Table 10. Product Specification

No.	Parts	Qty.	Material	Size (mm)
1	Housing	1	Stainless Steel	149.9 x 70.4 x 7.8
2	Display	1	OLED	147 x 68 x 1
3	Logic Board	1	Silicon Wafer	60 x 60 x 1
4	Battery	1	Lithium Ion	67 x 62 x 4
5	Speaker	1	Polycarbonate	37 x 31 x 4
6	Front Camera + Earpiece Speaker	1	Polycarbonate	19 x 13 x 6,8
7	Rear Camera	1	Polycarbonate	43 x 9 x 4
8	Component’s Screw	9	Stainless Steel	Dia. 1
9	Display’s Screw	2	Stainless Steel	Dia. 0.7

Figure 12. Final Prototype.

3.9. User Review

According to our research method, the last step would be to test our prototype. We ask 11 users to give a score based on the difficulty level from 1 (easy) to 5 (difficult).

Overall, all the users feel excited and could understand the disassembling process without any difficulty. With the average score of 1,8, it can be concluded that this prototype succeeds on being an easy-to-dismantle mobile phone.

Table 11. User Review

No.	Factor	A	B	C	D	E	F	G	H	I	J	K	Average
1.	Display disassembling difficulty	2	3	2	2	3	1	2	2	1	2	2	2
2.	Battery disassembling difficulty	1	2	1	1	3	1	1	1	2	2	1	1,4
3.	Speaker module disassembling difficulty	1	3	2	2	3	1	2	1	2	2	2	1,9
4.	Front camera + earpiece speaker disassembling difficulty	1	3	2	2	3	1	2	2	1	2	2	1,9
5.	Rear camera module disassembling difficulty	1	3	2	2	3	1	2	2	1	2	2	1,9
6.	Logic board disassembling difficulty	1	3	3	2	3	1	2	2	1	2	2	2
7.	User's understanding level	2	3	1	2	1	1	2	1	2	2	1	1,6
8.	Disassembly time level	1	3	1	1	3	2	2	2	2	2	2	1,9
Score													1,8

4. Discussion

From this research we can learn that an extremely complex and integrated parts in mobile phone are indeed one of the main obstacles in recycling process. With the change in architectural design, we can reduce the amount of time, effort, and materials in both production and waste management process. In addition, the interactive and intuitive design in both mobile phone and its packaging really helps the user in doing the disassembling process themselves. With that, we can conclude that waste problem can actually be solved by design innovation. In other studies, similar problem was executed using modular design mobile phone that can be repaired by the user. But in this study, we want to emphasize that user can also be a part of mobile phone's life cycle by sending it back to the producer. However, further study according various aspects need to be done, such as: wireless charging as the only charging feature and the elimination of volume control button. Not only that, but some parts of this mobile phone also might not be massed produced, therefore looking for the right vendor might be a challenge. In the future, we plan to do more analysis in user acceptance statistic according to their feedbacks and reviews. This can be done by doing more FGD (Focus Group Discussion) with targeted users to know what can be developed and whether our plan is on the right path or not.

Conclusion

The product innovation on this research is one of the best solutions for the mentioned problem. The easy-to-dismantle design succeed on solving the integrated and complex design problem on mobile phone. The intuitive and interactive design on both product and packaging succeed on solving the lack of user awareness problem. The design itself also succeed on applying the EPR concept in which solving the producer's irresponsibility problem. With that being said, this mobile phone concept has been in the right path and future development can be applied.

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Chapter 12

PURIFICATION OF WASTEWATER USING GRAPHENE DERIVATIVES

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ABSTRACT

Water is an essential substance for the survival of all living beings in this universe. However, water scarcity has been perceived as a growing challenge for humanity that demands global attention. More than one-third of freshwater available on the earth is used by agriculture, textile, meat production, beverage, and automotive manufacturing industries. As the world population and urbanisation continue to grow, the productions of the above sectors increase rapidly. Therefore, wastewater from these sectors has caused water pollution in more than 70% of the developing countries. Various harmful organic matters, heavy metals, radioactive materials, synthetic chemicals, and microorganisms are responsible for increasing water pollution and life-taking diseases.

This chapter has discussed graphene-based materials and their applications in treating wastewater. Over the past decades, graphene has been intensively studied because of its superior chemical, physical and mechanical properties. However, pristine graphene sheets are not suitable for water purification as they have limited dispersibility in an aqueous solution. Chemical modifications of graphene widely increase its dispersibility and applications in the purification of wastewater. Also, the emerging class of graphene derivatives has attracted significant research interest in water treatment.

The present chapter highlighted the purification of various organic, inorganic, and biological contaminants using graphene derivatives. Also, it discussed working principles of various graphene derivatives like graphene oxide, reduced graphene oxide, graphene sponge, functional graphene, inorganic graphene composite. In the end, the advantages

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and disadvantages of graphene derivatives are summarised, and the scopes of improvement are proposed.

ABBREVIATIONS

EDTA	Ethylenediaminetetraacetic acid
PDA	Polydopamine
Lys	Lysozyme
DMA	Dopamine methacrylamide
PDMS	Polydimethylsiloxane
PDDA	Poly Diallyldimethylammonium Chloride
PEI	Polyethyleneimine

INTRODUCTION

Water is one of the prominent natural resources on the earth, and it is available in useable form. Pure water is an odourless, tasteless and colourless essential substance for humans and other living beings; however, water scarcity has been perceived as a growing challenge for humanity that demands global attention. Around the world, about 4 billion people face an acute water shortage for at least one month per year (Mekonnen & Hoekstra 2016). Water scarcity is being influenced not only by pollution and climatic changes but also by poor water management.

As per the WHO report in July 2019, 785 million people lack access to purified drinking water, including around 144 million people who rely only on surface water. No less than 2 billion people globally use contaminated drinking water sources (Schwarzenbach 2006). According to the United Nations (UN) report, almost two-thirds of the world's population will face water scarcity by 2025 (Baer 2010). Clean and pure water is a primary resource for people's health irrespective of its use in drinking, domestic work and food production. The need for freshwater continues to grow, and demand persistently exceeds the supply. Water contamination is a critical problem for the world as it jeopardises human health and the economy. The prime reasons behind the water pollution are improper disposal of sewage, industrial waste, nuclear waste and agricultural pollutants, waste dumping in the marine, and oil spilling. The distribution of total available water on earth (El-Ghonemy 2012) and water demand to the various sectors in different countries (Cleemput & Saso 2017) are presented in Figure 1.

Continuous release of chemicals and toxicants mixed effluent from industries and municipalities contaminate the waterways. Organic matters (humic acids, fulvic acids, humins), heavy metals (mercury, lead, chromium), radioactive materials (uranium, caesium, plutonium), synthetic chemicals (pesticides, fertiliser, cosmetic), and water-borne pathogens (bacteria, virus, protozoa) are the common water contaminants. The spilling of oils and hazardous chemicals pollute the water and destroy marine life and the ecosystem (Matilainen et al. 2010). Sources and effects of various contaminants are summarised in Table 1.

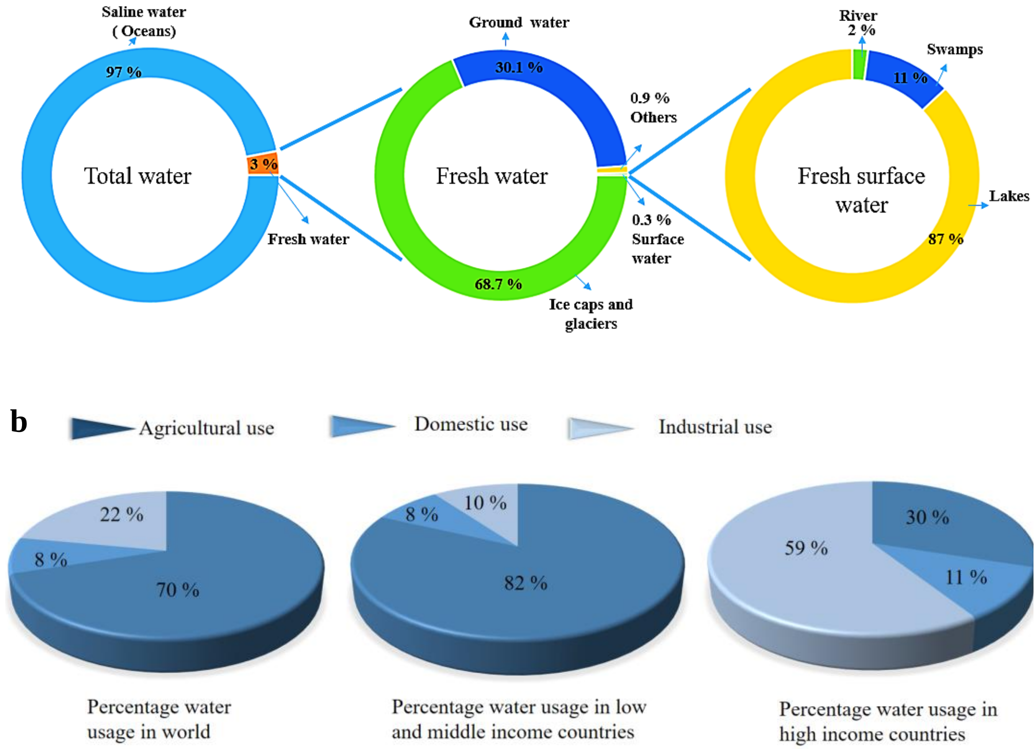

Figure 1. (a) Total water distribution on earth and (b) comparative study on water demand to various sectors.

Table 1. Various water contaminants with sources and effects (Matilainen et al. 2010)

Water Contaminants	Sources of Contaminants	Effects of Contaminants
Pathogen	Bacteria Viruses	Water-borne diseases
Agricultural Contaminants	Chemicals used in agriculture	Direct effect on the freshwater resources
Sewage and contaminated water	Wastewater from domestic use	Water-borne diseases
Nutrients Contaminants	Fertilisers and Plant debris	The eutrophication process gets affected
Radioactive contaminants	Different isotopes	Effect on Bones, teeth, skin
Industrial contaminants	Municipal pollutant water	Caused water and air pollution
Organic Contaminants	Detergents, insecticides, herbicides	Aquatic life problems, cacogenic
Macroscopic Contaminants	Marine debris	Plastic pollution
Sediments and suspended solids	Land cultivation, demolition, mining operations	Damage to fish spawning and effect on the aquatic environment of fishes and insects
Inorganic Contaminants	Metal compounds, trace elements, mineral acids, heavy metals, inorganic salts	Public health problems and aquatic flora and fauna,

Hazardous chemicals present in polluted water cause adverse effects on health, including immune suppression, acute poisoning, neurological disorder, organ damage and fluorosis. Radioactive materials cause cancer, cardiovascular disease, etc. Oil spill reduces the oxygen level in the water, resulting in dead zones without aquatic life. At the same time, diseases like cholera, diarrhoea, typhoid, dysentery and hepatitis-A are caused by pathogens present in water (Forstinus et al. 2016). As per the WHO report, around 829000 people die each year because of various water-borne diseases.

The conventional technologies for wastewater treatment involve various basic methods like boiling and desalination (Shatat & Riffat 2014), physical methods like settling and filtration (Mehmood et al. 2019), chemical methods like disinfection and coagulation (J.-Q. Jiang 2015), and biological methods like anaerobic digestion (Hanum et al. 2019) and membrane aerated biofilm reaction (Nerenberg 2016). Since the early 20th century, the most extensively used water treatment technology has involved coagulation followed by sedimentation and filtration.

Conventional water treatment processes remove organic compounds, sediments, inorganic matters and suspended solids. The natural organic matter (NOM) existing in water creates various problems during conventional treatment methods like coagulation. Also, traditional methods have certain limitations in the elimination of micro-pollutants (Hofman-Caris & Hofman 2017). Ozone and chlorine are widely used in the disinfection process, but both chemicals are known for forming harmful by-products. Chlorine forms chlorinated organic compounds, and ozonation forms carcinogenic organo-brominated compounds (Martinez et al. 2011). Currently used disinfection technologies such as UV (Ultraviolet) and H_2O_2 treatments result in an increment of genotoxic activity (Metz et al. 2011). Nowadays, the main challenge for surface water is the emergence of new synthetic chemicals and microorganisms, which are not often monitored in the water but have vast potential to cause adverse environmental and health effects. Some of them are illicit drugs, complexing agents, sweetening agents, products for personal care, pesticides, flame retardants, perfluorinated compounds, nanoparticles, fuel additives, and endocrine-disrupting compounds. Even though conventional water purification methods are constantly being improved and upgraded for efficient removal of contaminants in a cost-effective process, removal of emerging contaminants becomes challenging by these traditional methods (Hofman-Caris & Hofman 2017). Nowadays, advanced treatment technologies are gaining popularity, but they are costly and not able to remove emerging substances entirely. European inventory of existing commercial chemical substrates (EINECS) has registered more than 100000 emerging chemicals, out of which 30000-50000 are in daily use (Schwarzenbach 2006). Researchers have put their effort into developing alternative water treatment technologies such as membrane filtration (RO purifiers) (Zularisam et al. 2006), UV irradiation method (e-boiling) (Amirsardari et al. 2001), and advanced oxidation processes (AOPs) (O'Shea & Dionysiou, 2012) to remove emerging water pollutants.

The newly emerging field of nanotechnology has drawn wide attention due to its extensive usage in catalysis, medicine, sensing and wastewater treatment (Bano et al. 2020; Machado & Serp 2012; Saha et al. 2017, 2018; Y. Yang et al. 2013). Nanoparticles hold promising application prospects in wastewater purification because of their high reactivity, large surface area, strong solution mobility, high mechanical strength, variable hydrophilicity, high porosity and fast dispersibility. Additionally, removals of various heavy metals, organic and inorganic contaminants and harmful bacteria are possible using various nanomaterials.

Two-dimensional (2D) graphene sheets have been found to be a miracle in the domain of water filtration because of their unique structure and selective permeability that limit diffusion of unwanted metals, chemicals, and microbial pathogens but allow water molecules (Romaniak et al. 2020). Pure graphene has limited applications in water purification as it repels water, but graphene sheets perforated with miniature holes enable water to pass through them and block the passage of contaminants. Graphene composites act as adsorbents in removing organic pollutants, heavy metals and emerging chemicals. Additionally, the electron-accepting ability of graphene-based materials widens their applications as a catalyst in activating oxidising agents for degrading the organic pollutants present in water (Gandhi et al. 2016). Graphene oxides (GO) and reduced graphene oxide (rGO) allow water molecules to pass through the nano capillaries but restrict metals, ions, gases and chemicals; therefore, they have been used as molecular sieves. (Y. Dong et al. 2019; B. Mi 2014; Prince et al. 2016). GO is a form of graphene that has been oxidised with hydroxyl, carbonyl, and epoxy functional groups. These functional groups help in stacking GO sheets with optimised interlayer spacing, charges and functionalities. However, GO membranes with interlayer spacing larger than 0.7 nm perform poorly in the desalination of hydrated Na^+ ions (radius: 0.36 nm) (Dervin et al. 2016). Also, the transfiguration of GO in water over a long period limits its performance in water purification. At present, the bulk production of large sheets of single-layer graphene films without considerable flaws is a challenging task. Defects like grain boundaries in graphene sheets affect interlayer distance, mechanical stability and selectivity and compromise the performance in desalination (K. Yang et al. 2018). Apart from all the above, the limited availability of graphene and the presence of cheap alternatives slow down the move to graphene-based water purifiers.

GRAPHENE AND ITS DERIVATIVES

The Functionality of Graphene/Derivatives as Filtering Materials

Graphene is a fascinating 2D carbon sheet having single-layered atom thickness endowed with distinctive chemical and physical properties. In water purification, graphene and graphene derivatives have shown promising performance as adsorbent, membrane, catalyst (electrocatalyst, photocatalyst, photo electrocatalyst), disinfectant and desalination agent. Graphene derivatives undergo various interactions with water molecules and contaminants during filtration. Possible interactions between pollutants and graphene derivatives are schematically shown in Figure 2.

Electrostatic Interaction

Electrostatic interaction is one of the primary forces that causes GO and its composites to adsorb cationic contaminants. As per the structure, GO surfaces have negatively charged oxygen-containing groups; therefore, they prefer binding with positively charged impurities such as heavy metal ions and cationic dyes. GO displays excellent performance in a basic environment due to the enhanced deprotonation of the carboxyl group. Various researches have shown GO has a pH-dependant adsorption capacity of cationic contaminants. A high pH value facilitates the excellent removal of methylene blue (MB) by GO and its derivatives (S.-T. Yang et al. 2011; Bano et al. 2020; Saha et al. 2017). The metal ions and pi electrons also show electrostatic interaction along with the chemical interaction. As for the negatively charged contaminants, GO and its composites are not favoured because of the electrostatic repulsion. It has been found that GO has high adsorption affinity for MB and cationic dyes than negatively charged dyes. GO has shown 90% efficiency in treating cationic dyes;

whereas, the removal efficiency of GO is almost negligible in the case of anionic dyes (Sabna et al. 2018; Sharma & Das 2013). Therefore, reduction or modification of GO with -NH_2 groups is recommended to control electrostatic repulsion and enhance the removal capacity of anionic dyes (Ramesha et al. 2011). Electrostatically interacted impurities remain on the adsorbent surfaces for a long time and reduce the separation efficiency of recycled GO. Researchers have tried various methods to improve the adsorption efficiency of recycled GO. The MB desorption efficiency of GO was found to be below 40% even after acetic acid wash; whereas, it can be significantly improved by an acid wash using HCl at pH 1 (Madadrang et al. 2012; S. T. Yang et al. 2010). A strong electrostatic interaction between pollutants and graphene adsorbents should be avoided considering the complex recycling procedure. The important thing is to have a good balance between adsorption capacity and recyclability of adsorbents.

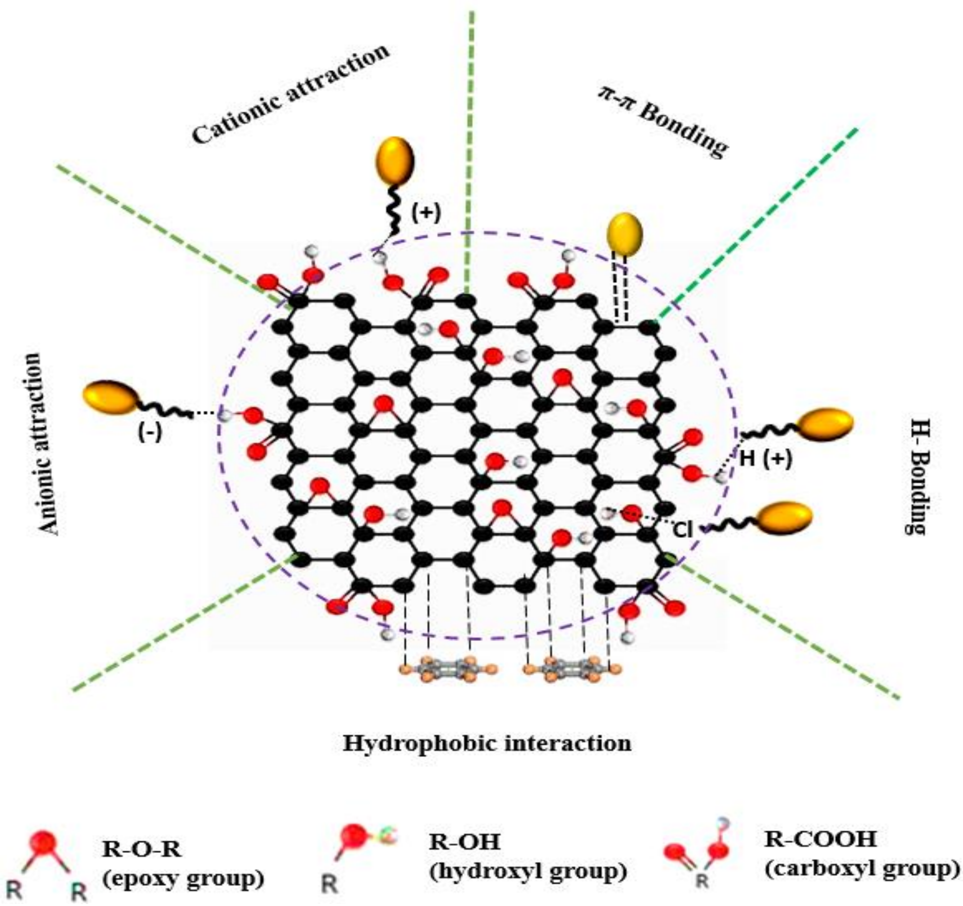

Figure 2. Various molecular interactions between graphene and pollutants.

Pi-Pi Stacking

Aromatic rings form pi-pi interactions with graphene sheets. Experimental results and computational studies show that the pi-pi interactions have profound existence and significant contribution towards the interaction between sp^2 carbon nanomaterials and aromatic pollutants (S.T. Yang et al. 2008). Studies on carbon nanotubes (CNT) have extensively discussed similar binding between sp^2 carbon and pollutants. So considering the similarities between CNT and graphene structure, pi-pi stacking is of utmost importance interaction in enhancing the adsorption performance of graphene. The pi-pi interaction has been found to be weaker than the electrostatic interactions when ionic groups are present in the pollutants. At the same time, electrostatic interaction facilitates a high attractive force between carbon structure and MB; thus, GO shows better MB adsorption capacity than graphene, reduced graphene and CNTs (S. T. Yang et al. 2010).

Hydrophobic Interaction

The hydrophobic interaction causes adhesion, aggregation and flocculation among various hydrophobic molecules. Hydrophobic surfaces of graphene and reduced graphene make them a potential candidate for the removal of aromatic pollutants and oils. The hydrophobic interaction happens between the hydrophobic parts of contaminants and the graphene.

Coordination Bond

Although coordination bonds have been discussed less, they play a significant role in removing metal ions from water. Oxygen atoms present on the GO surfaces form coordination bonds with metal ions. In an aqueous solution, GO can be folded/aggregated by Cu^{2+} ions with excellent adsorption capacity. This folding is generally triggered by coordination bonds between GO and copper ions, as shown in Figure 3. A comparative study on the folding/aggregation of GO by Cu^{2+} and Na^+ showed that Cu^{2+} has high binding affinity than Na^+ in the same ionic strength. Spectrum shift of UV-Vis spectrometer can confirm the formation of coordination bonds between folded GO and Cu^{2+}. The above results suggest that coordination bonds should be considered and designed during the purification of heavy metal ions by GO (Hofman-Caris & Hofman 2017). Similar attempts have been made in CNTs, where - SH groups are attached to the carbon skeleton to facilitate the chelation of Cd^{2+} (Y. Liu et al. 2008).

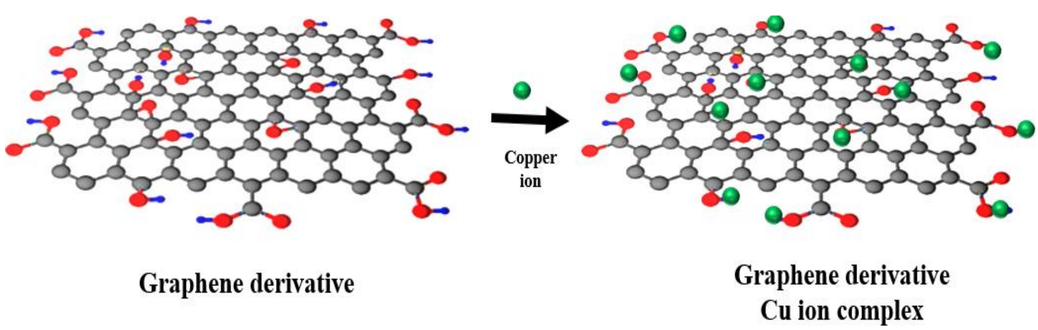

Figure 3. The schematic diagram shows the coordination interaction between GO and Cu^{2+} ions.

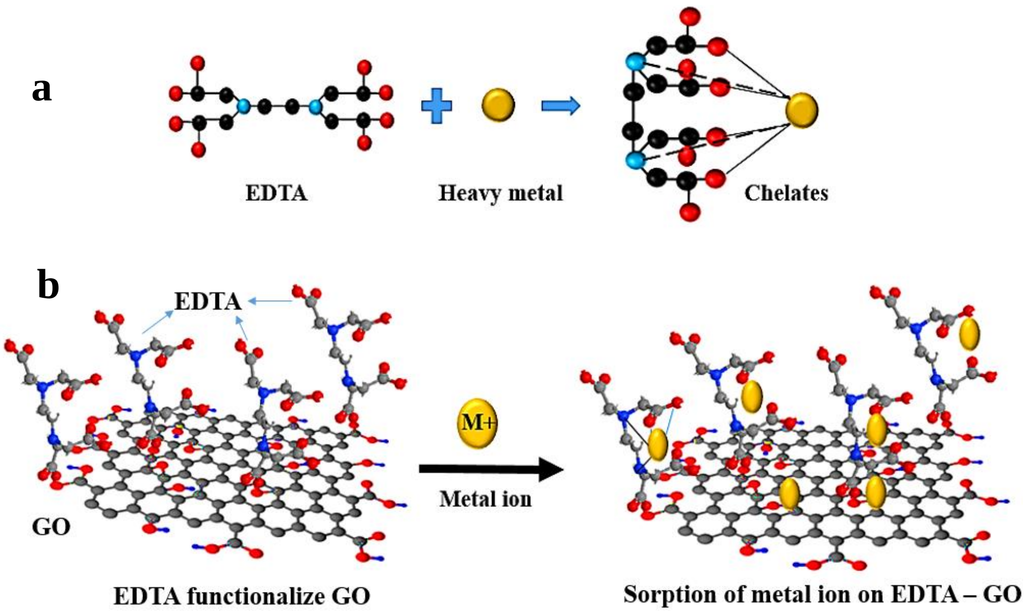

Figure 4. (a) Chemical structure of EDTA and its chelating effect and (b) chemical structure of EDTA functionalised graphene derivative (left) and its interaction with heavy metal cations (right).

Various researchers have demonstrated the attachment of EDTA to GO surfaces by silylation (Madadrang et al. 2012), as shown in Figure 4(a). Typically, EDTA is used as a chelator to remove metal ions (Muthusaravanan et al. 2020). Metal ions such as Pb^{2+}, Ni^{2+}, Cu^{2+}, Cd^{2+}, and Hg^{2+} experience chelation by EDTA present on GO, as illustrated in Figure 4(b). Thus, GO-EDTA improves the adsorption capacities of heavy metal ions significantly.

In a recent development, GO has been functionalised using cyanobacterium metallothionein, a cysteine-rich protein that coordinates with Cd^{2+} to bind with GO composite (T. Yang et al. 2012). The sulfhydryl groups found in cysteine coordinate with Cd^{2+} and bind on GO surfaces.

Further Interactions

The H-bond provides hydrogen donor-acceptor interaction. The -OH and –COOH functional groups presence in GO and its composites produce H-bond with the polar atoms belonging to the pollutants such as O, S and N. In addition, water molecules in an aqueous solution provide the hydrogen donors/acceptors. Therefore, even when the H-bond is quite strong and in the range of 5–30 kJ/mol, the total contribution of H-bond in removal of impurities is negligible. Other than H-bond, Van der Waals interactions contribute to the adsorption of pollutants by graphene. Van Der Wall forces are weak attraction forces that work between close-packed neutral molecules, and they rapidly decrease with an increase in distance between molecules. Hence, Van Der Wall forces have a minuscule contribution in the adsorption of pollutants by graphene.

APPLICATION OF GRAPHENE DERIVATIVES IN WASTE WATER TREATMENT

Removal of Different Pollutants Using Graphene and Its Derivatives

Purification of Organic Contaminants

Graphene-based constituents are excellent adsorbing materials; hence, they can be used in removing numerous pollutants such as pesticides, organic dyes, toxic chemicals, pharmaceutical drugs, pesticides and various oils like paraffin, gasoline, and vegetable oils (Baig et al. 2019; Carmalin Sophia et al. 2016; Lazarevic-Pasti et al. 2018; L. Xu & Wang 2017). Also, organic contaminants like hydrocarbons, antibiotics, dyes, and natural organic matter are removed from water using graphene-based constituents as adsorbents. The organic pollutants are removed by pi-pi interaction, hydrogen bond, electrostatic interaction, cation-pi interaction, anion-pi interaction and anion-cation interaction with functional groups present in GO surfaces. Experimental results show that Van der Waals interaction effectively removes anionic and cationic dye (F. Liu et al. 2012). Electrostatic interaction is the primary mechanism in removing pollutants with charged functional groups since the GO derivatives have polar terminals. The cationic dyes like methyl violet and methylene blue are adsorbed through electrostatic interaction between the dye molecules and the GO. However, adsorptions of orange G, acid orange 10, azo dye, and other anionic dyes are not favourable due to the repulsion between the dye molecules and the negatively charged functional groups present in GO (F. Liu et al. 2012). At the same time, the adsorption of cationic dyes is accredited due to pi-pi interactions. Researchers have found that the most effective mechanisms for the removal of methyl violet and methylene blue from water using 3D-GO sponges are anion-cation interaction and pi-pi stacking (F. Liu et al. 2012). The spongy graphene showed greater competence in excluding petroleum waste from oil-water mixture than conventional adsorbents (C. Ji et al. 2017; T. Liu et al. 2015; Y. Luo et al. 2017). Also, spongy graphenes can be scaled up for large-scale production and can be renewed easily by heat treatment. Some researchers have used magnetic GO to filtrate organic pollutants (Lingamdinne et al. 2019). Initial oxidation of graphene results in the formation of hydroxyl groups on the basal plane and the edges of graphene, whereas further oxidisation causes the formation of ketone and quinine groups on the edges and formation of epoxide groups on the basal plane (H. Wang et al. 2013). Therefore, the adsorption mechanisms shift from pi-pi stacking to electrostatic interactions with an increase in oxidation degree of graphene-based materials.

The rGO-based materials increase the adsorption efficiency of anionic dyes, whereas they do not affect cationic dye adsorption capacity. The probable interactions of the dyes with GO and rGO are presented in Figure 5. Electrostatic interactions and Van der Waals interactions play critical roles in the adsorption of aromatic rings; hence, GO/graphene composites process excellent efficiency in removing the methylene blue (B. Li et al. 2011). Besides removing dye from water, GO/graphene can also be used to adsorb various organic contaminants. Also, GO can remove the tetracycline through cation-pi bonding and pi-pi interaction (Y. Gao et al. 2012). The pi-pi exchanges and formation of hydrogen bonds are credited for removing Bisphenol-A from water using graphene (J. Xu et al. 2012). Hydrogen bonds play a crucial role whenever amine and hydroxyl functional groups take part in the adsorption. Hence, GO-based composites adsorb polar hydrocarbons such as naphthalene by the formation of hydrogen bonds. On the other hand, hydrophobic interactions are responsible for the adsorption of non-polar hydrocarbons by the graphene sheets and rGO because of their hydrophobic surfaces (Perreault et al. 2015). Table 2 shows some examples of graphene-based materials for the adsorption of organic contaminants.

Adsorption of Inorganic Contaminants

Graphene-based nanomaterials can be used to adsorb various inorganic contaminants such as radionuclides, anionic pollutants and heavy metals. The inorganic pollutants are removed by graphene-based material through electrostatic interaction, physical adsorption, and precipitation (H. Wang et al. 2013). The adsorption capacity of thermally modified graphene nanosheets (GNSs), and pristine GNSs were tested for Lead (Pb(II)) (Huang et al. 2011). The comparative study showed that heat treatment enhanced the Pb(II) sorption capacity of GNSs due to improvement in Lewis basicity and electrostatic attraction. Nevertheless, graphene-based adsorbents show low metal cations adsorption capacity, which is improved by polyphenols functionalisation of GNSs (Song et al. 2012). Biodegradability, low toxicity, and water solubility are few advantages of tea polyphenols functionalised GNSs (Zhu et al. 2012). Researchers have discovered that the Pb(II) sorption capacity of tea polyphenols functionalised GNSs is as high as 1126mg/g. Researchers have developed magnetic graphene nanosheets for ease of separation of graphene after use. Even though magnetic graphene nanosheets have high adsorption capacity and magneticity of iron oxide nanoparticles, their applications are not practical in continuous flow systems.

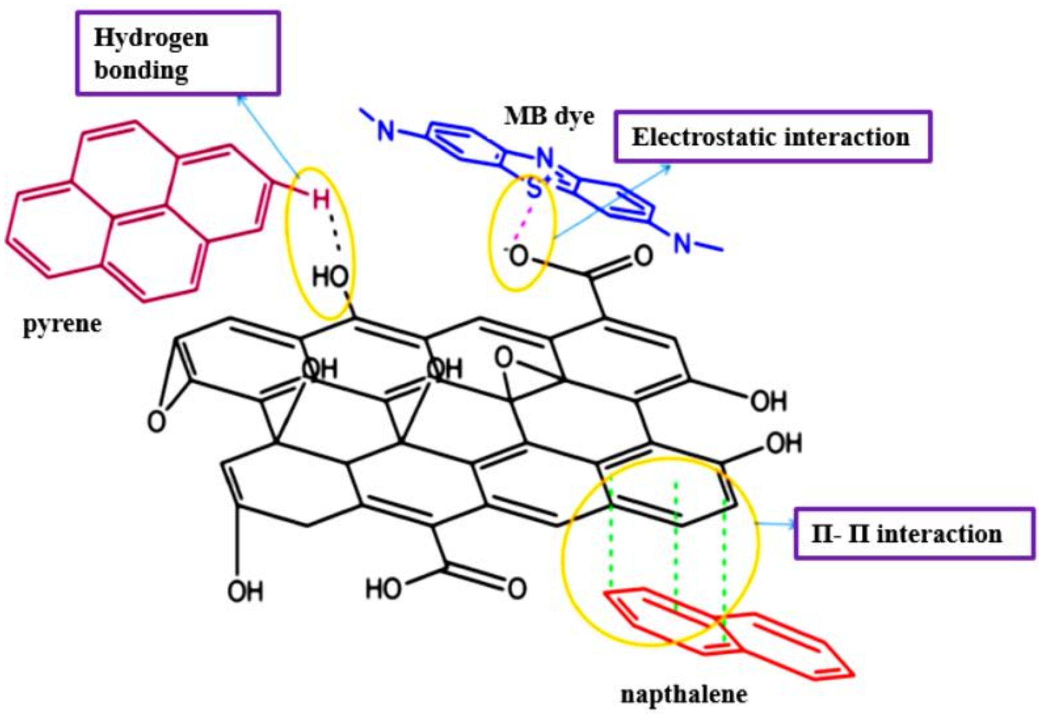

Figure 5. Removal of various organic pollutants using graphene derivatives (Thakur & Kandasubramanian 2019).

Table 2. Graphene-based materials for adsorption of organic contaminants

Composite	Pollutants	Adsorption capacity	Reference
Graphene	Methylene blue 1-napthalene sulfonic acid	153.85 mg/g 1.5 g/g	(Yao et al. 2012) (T. Wu et al. 2011)
GO	Methylene blue Methylene green naphthalene pyrene	714 mg/g 93% 21.4 mg/g 1.05 mmol/g	(Perreault et al. 2015) (Sharma et al. 2014) (Kyzas et al. 2015) (Kyzas et al. 2015)
rGO	Methylene green Naphthalene Pyrene Anthracene Bisphenol A	77% 46.132 mmol/g 4.842 mmol/g 1.028 mmol/g 181 mg/g	(Sharma et al. 2014) (Y. Sun et al. 2013) (Y. Sun et al. 2013) (Y. Sun et al. 2013) (J. Xu et al. 2012)
rGO based hydrogel	Methylene blue Rhodamine B	100% 97%	(H. Guo et al. 2015) (H. Guo et al. 2015)
Chitosan /GO	Methylene blue Methylene orange	1.6 mmol/g 0.8 mmol/g	(B. Zhang et al. 2018) (B. Zhang et al. 2018)
rGO-TiO_2 hybrids	Methylene blue	90%	(Nguyen-Phan et al. 2012)
Magnetite rGO	Rhodamine B Malachite green	91% 94%	(H. Sun et al. 2011)
rGO-Fe_3O_4	Malachite green Rhodamine 6G	50 mg/g 30 mg/g	(Geng et al. 2012)
GO- Fe_3O_4 hybrid	Methylene blue	167.2 mg/g	(Xie et al. 2012)
Magnetic chitosan-GO	Methylene blue	95.16 mg/g	(Fan et al. 2012)
PDA-GO	Methylene blue	2.18 g/g	(Z. Dong et al. 2014)

Several factors affect the heavy metal adsorption capacity of GO, such as pH, ionic strength, and the number of oxygen groups (Sitko et al. 2013). Experimental results showed that GO has the optimised adsorption capacities of 530, 294, 1119, and 345 mg/g for removal of Cd^{2+}, Cu^{2+}, Pb^{2+}, and Zn^{2+}, respectively at pH 5 (Sitko et al. 2013). At the same time, GO has an adsorption capacity of 68.2 mg/g for Co^{2+} and 106.3 mg/g for Cd^{2+} in an aqueous solution (Zhao, Li, et al. 2011). A solution pH higher than pH_{pzc} (point of zero charge pH) triggers the deprotonation of oxygen-containing functional groups present on GO surfaces. This effect favours the electrostatic interactions of positively charged metal ions with GO and enhances the adsorption capacity of GO (Sitko et al. 2013). Some researchers have suggested alternative mechanisms other than electrostatic interactions between GO and oxygenated functional group of metal ions contributing to the metallic adsorption. They have proposed that the delocalised pi electrons of the sp^2 network of graphene contribute e^- to the positively charged metallic ions and act as a Lewis base. Adsorption of the heavy metal ions on few-layered graphene oxide (FGO) is mainly caused by outer-sphere surface-complexation at low pH; whereas, the adsorption of the metal ions is caused by inner-sphere surface complexation at high pH (Zhao et al. 2011). Experimental results showed that Eu (III) binds with seven oxygen atoms with a bond distance of around 2.44°A in the first coordination shell, indicating the formation of inner-sphere complexation on FGO (Y. Sun et al. 2012). Apart from adsorption of Eu (III), graphene-based materials are efficient in removing phosphate (PO_4^{3-}), fluoride (F^-), perchlorate (ClO_4^-), and many other anionic pollutants (Y. Li et al. 2011; Shi et al. 2012; Vasudevan & Lakshmi 2012; S. Zhang et al. 2011). The adsorption mechanism of anions on graphene is mainly accredited to anion-pi interactions, which occur because of the interaction among anion and electro-deficient aromatic rings present in graphene layers (Shi et al. 2012). The binding mechanism of inorganic contaminants with GO and their removal methodology from wastewater are shown in Figure 6. Table 3 summarises the adsorption capacities of various graphene-based materials for various inorganic pollutants.

Table 3. Graphene-based materials for adsorption of inorganic contaminants

Composite	Pollutants	Adsorption capacity (mg/g)	Reference
Graphene	F^- PO_4^{3-}	17.65 89.37	(Y. Li et al. 2011) (Vasudevan & Lakshmi 2012)
GO	Am (III) Co (II) Cd (II) Cu (II) Sr (II) U (VI) Th (IV) Zn (II) Pb (II)	8.5 68 106 47 24 98 411 345 842	(X. Ren et al. 2013) (W. Zhang et al. 2011) (W. Zhang et al. 2011) (S. T. Yang et al. 2010) (Romanchuk et al. 2013) (Zhao et al. 2012) (Pan et al. 2013) (Sitko et al. 2013) (Sitko et al. 2013)
rGO	Fe (II)	299	(Chang et al. 2013)
$rGO/Fe_3O_4/MnO_2$	As (III) As (IV)	14 12	(X. Luo et al. 2012) (X. Luo et al. 2012)
$GO/Fe_3O_4/\beta$-CD	Cr (VI)	120	(Fan, Luo, Sun, et al. 2012)
$rGO/CoFe_2O_4$	Hg (II)	158	(Y. Zhang et al. 2014)
rGO/β-MnO_2	Ni(II)	47	(Y. Ren et al. 2011)
Magnetite rGO	As (III)	13	(Chandra et al. 2010)

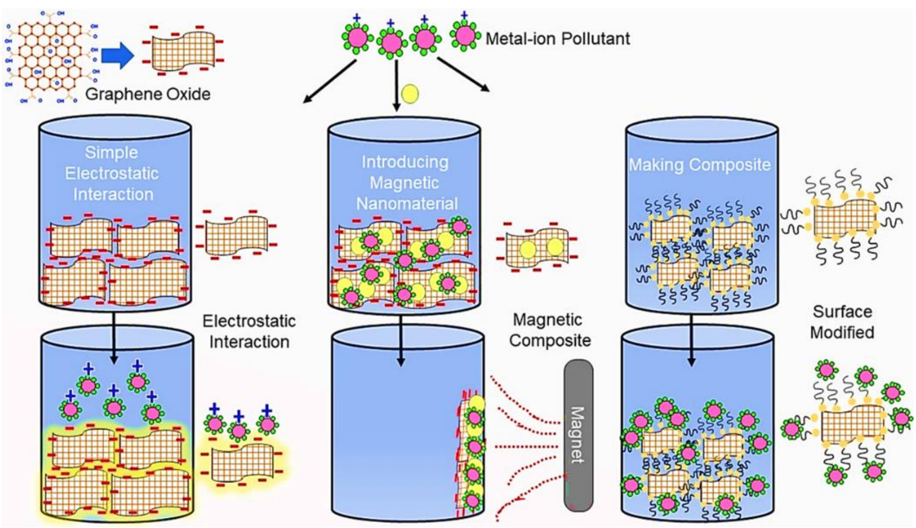

Figure 6. The schematic diagram shows the removal mechanism of heavy metal using magnetic graphene derivative (Velusamy et al. 2021).

Adsorption of Biological Contaminants

Control on the growth of bacteria proves to be a challenging task in most wastewater treatments because of biofilm formation on the filter. Recently, researchers have found that graphene and its derivatives have promising anti-microbial activity because of their surface-specific interactions (Kumar et al. 2019). Various antibacterial mechanisms of graphene-based materials are shown in Figure 7 (Xia et al. 2019). The breaking of cell walls due to direct contact or photo-induced degradation is responsible for the anti-microbial effects of graphene (Perreault et al. 2015). The anti-microbial mechanism of GO includes punctuation of cellular envelope by sharp flakes, extraction of phospholipids, disruption of deoxyribonucleic acid (DNA), proteins by reactive oxygen species (ROS) generation, and covering of cell by large flakes. Even though small sheets have a better cutting effect, they cannot trap the cells (Mao et al. 2014). The increase in the lateral dimension of graphene sheets increases the wrapping of cells, leading to a rise in the anti-microbial effect. In comparison to graphene and rGO, GO has a large number of functional groups that provide strong interaction with the cell sides and increase anti-microbial activity.

Furthermore, the processes of generating ROS and oxidative stress happen to be antibacterial mechanisms. Higher oxidative stress is observed in GO exposed cells as compared to the rGO coated cells because of the colloidal stability of GO. Additionally, the process of O_2 adsorption on the edges and defect sites of GO has played a crucial role in generating ROS (Perreault et al. 2015). However, comparative efficacies of conductive nanosheets (rGO and graphene) and insulating nanosheets (GO) are contradictory.

Various anti-microbial composites are synthesised using graphene nanomaterials. Conventional anti-microbial materials such as polymers, metals, phosphonium salts and metal nanoparticles are combined with graphene to improve their anti-microbial properties. Graphene is used to support the dispersion and stabilisation of various nanomaterials in achieving high antibacterial activity. GO-CdS composite shows high antibacterial efficacy against Gram-positive B. subtilis and Gram-negative E. coli, and it kills nearly 100% bacteria in 25 min of treatment (P. Gao et al. 2013). Silver (Ag) has been studied extensively in the preparation of graphene-based anti-microbial nanocomposites. Ag ions can penetrate the bacterial cell membranes and inactivate the enzymes; however, Ag-NPs aggregate upon bacterial contact and lose their active area. The above challenge can be overcome by synthesising Ag nanocomposites with graphene-based materials. Copper (Cu) can also act as an inexpensive antibacterial agent; however, Cu alone is inefficient because of its aggregation. An rGO-Au hybrid can also be prepared by anchoring AuNPs on rGO planes. These graphene-based novel nanocomposites exhibit excellent water dispersibility and efficient anti-microbial effects (H. Ji et al. 2016).

At the same time, graphene enhances the efficiency of conventional photocatalyst disinfectants. rGO-TiO_2 thin films display a 7.5 times higher antibacterial activity than the TiO_2 films under solar light irradiation (Akhavan & Ghaderi 2009). Even in the absence of light, AgNP/GO and Ag-GO-TiO_2 composites demonstrate excellent ability to deactivate S. aureus, E. coli, and B. subtilis by 87.6% – 100% (Bao et al. 2011; Y. Jiang et al. 2016). Also, 2D and 3D graphene hydrogels have been utilised for the disinfection of bacteria. E. coli removal efficiency of 2D and 3D Ag/rGO hydrogel-based filters is about 98% (Zeng et al. 2015).

It has been observed that nanocomposite of 3 wt% graphene and polyvinyl-N-carbazole (PVK) archives similar anti-microbial efficacy of 100 wt% graphene. The graphene-PVK nanocomposite has been used as a surface coating to prevent bacterial growth and bio-fouling. This graphene nanocomposite can reduce the cost of adsorbents and impact on the environment associated with graphene usage (Perreault et al. 2015). However, the antibacterial mechanism of graphene is not entirely understood yet.

Table 4. Graphene-based material for the treatment of biological contaminants

Composite	Species	Removal (%)	Reference
GO	*S. aureus/ P. aeruginosa*	93.7/45	(Kumar et al. 2019)
GO Nano walls	*E. coli*	74	(Akhavan & Ghaderi 2010)
GO-Ag NPs	*E. coli/ S. aureus*	100	(Akhavan & Ghaderi 2010)
GO-Ag_3PO_4 NPs	*E. coli/S aureus*	92.8/100	(Trench et al. 2020)
GO-EDTA	*C. metallidurans* *B. Subtilis*	99.1 92.3	(Akhavan & Ghaderi 2010)
GO-ZnO	*E. coli*	100	(Kavitha et al. 2012)
GO-CdS	*E. coli/ B. subtilis*	100	(P. Gao et al. 2013)
GO-Fe_3O_4	*E. coli*	91.5	(Deng et al. 2014)
GO-Fe_2O_3	*E. coli*	97	(Santhosh et al. 2014)
GO-Mn-Fe_2O_4	*E. coli*	82	(Duguet et al. 2015)
GO-Bi_2WO_6	*Mixed culture*	100	(Chen et al. 2015)
GO-Lys	*E. coli*	68	(Duan et al. 2015)
PDMS-GO-DMA	*E. coli/S. aureus*	40	(Tu et al. 2019)
rGO	*E. coli*	88	(Gurunathan et al. 2013)
rGO	*P. aeruginosa*	100	(Gurunathan et al. 2012)
rGO-Ag NPs	*E. coli*	100	(Moghayedi et al. 2017)
rGO- ZnO	*E. coli*	100	(Kavitha et al. 2012)
rGO-Cu_2O	*E. coli/S. aureus*	70/65	(Z. Yang et al. 2019)
rGO-Ag NP-PDDA	*E. coli*	100	(J. Shen et al. 2012)
GO-Ag-$CoFe_2O_4$	*E. coli/ S aureus*	97/99	(Ma et al. 2015)
rGO-PEI-Ag NPs – Fe_2O_3	*E. coli*	99.9	(N. Wang et al. 2015)

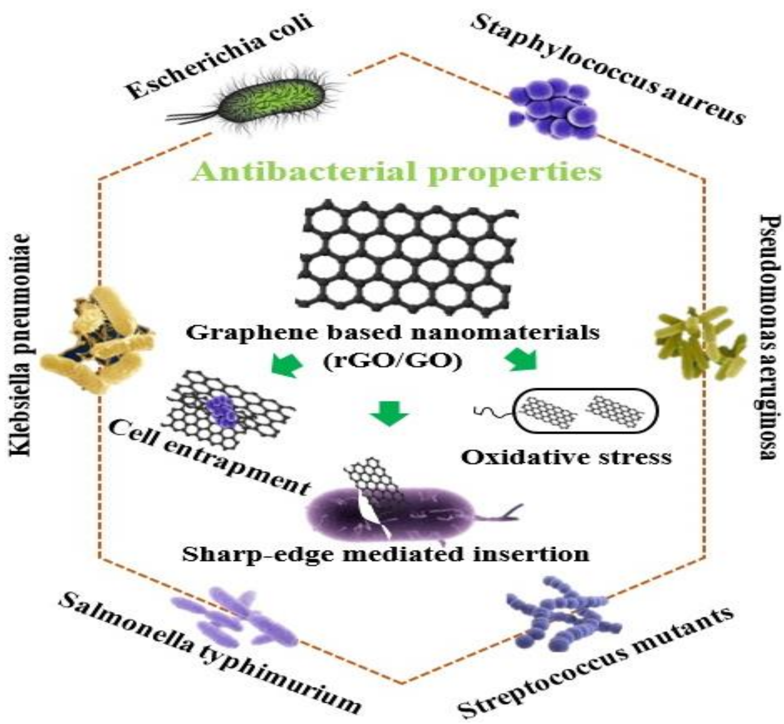

Figure 7. Antibacterial activities of graphene-based materials.

Researchers are working to identify the determinant factors responsible for antibacterial activity, including physical characteristics, chemical factors, edges effect and the basal planes (Akhavan & Ghaderi 2009). Also, researchers are focusing on the development of innovative graphene derivatives that can overcome present shortcomings. Various graphene-based materials that have been used for the removal of biological contaminants are presented in Table 4.

GRAPHENE DERIVATIVES

Graphene Oxide

GO is the most significant adsorbent because of its superior performance, lower cost, and ease of processing. Figure 8 illustrates the basic structures and synthesis processes of graphene, GO, and rGO (Jimenez-Cervantes et al. 2016; Priyadarsini et al. 2018). Usually, GO is synthesised by modified Hummer's method using graphite as a precursor and $NaNO_3$ and H_2SO_4 as oxidising agents (El-Shafai et al. 2018). $KMnO_4$ is added to the mixture for further oxidisation of the graphite precursor. After that, the reaction of the excess $KMnO_4$ is terminated by the addition of H_2O_2. Finally, the mixture is sonicated to produce single-layered and few-layered GO. Hummer's method has been modified to improve the production capacity of single-layered and few-layered graphene. Various researchers have performed pre-oxidation using P_2O_5 and $K_2S_2O_8$ into the H_2SO_4 solution (Kovtyukhova et al. 1999). After the addition of $KMnO_4$, the reaction temperature and oxidation rate are controlled using an ice bath. A slow oxidation rate allows the insertion of enough oxygen in between graphite layers. After that, H_2O_2 is used to kill the reaction and remove excessive $KMnO_4$. Single-layered GO sheets are formed by vigorous sonication of the mixture.

The drying of GO should be planned cautiously. Direct drying of GO produces a paper-like structure with tightly stacked GO flakes (Mishra & Ramaprabhu 2011). These paper-like structures are not preferred for wastewater purification as the tightly packed layers limit the diffusion and adsorption of contaminants. Lyophilization extracts water molecules and creates a porous structure by sublimation; therefore, this process is popular for drying GO. Additionally, GO suspension displays the great potential for adsorption of impurities and the quickest kinetics (F. Liu et al. 2012).

Reduced Graphene Oxide

Another essential graphene-based adsorbent is rGO, which has fewer oxygen atoms in graphene basal planes than GO. rGO is prepared in two ways: the first method is the direct growth of rGO, and the second process is the reduction of GO. The second methodology is simple, cost-effective, rapid, scalable and suitable for water purification. Figure 9 states the various reduction methods to produce rGO from GO (Feng et al. 2020). The extensively used method for the reduction of GO is chemical reduction. Researchers have explored various reducing agents for the removal of oxygen groups from GO. Hydrazine is a widely used chemical because of its rapid oxidation rate and high power density. Other well-known reducing agents are $NaBH_4$ and $Na_2S_2O_3$. Another emerging rGO production route is plasma reduction of GO, where GO is treated by a radio frequency inductively coupled plasma (Q. Wang et al. 2013). The plasma reduction occurs at a low temperature; therefore, it generates low stress on support.

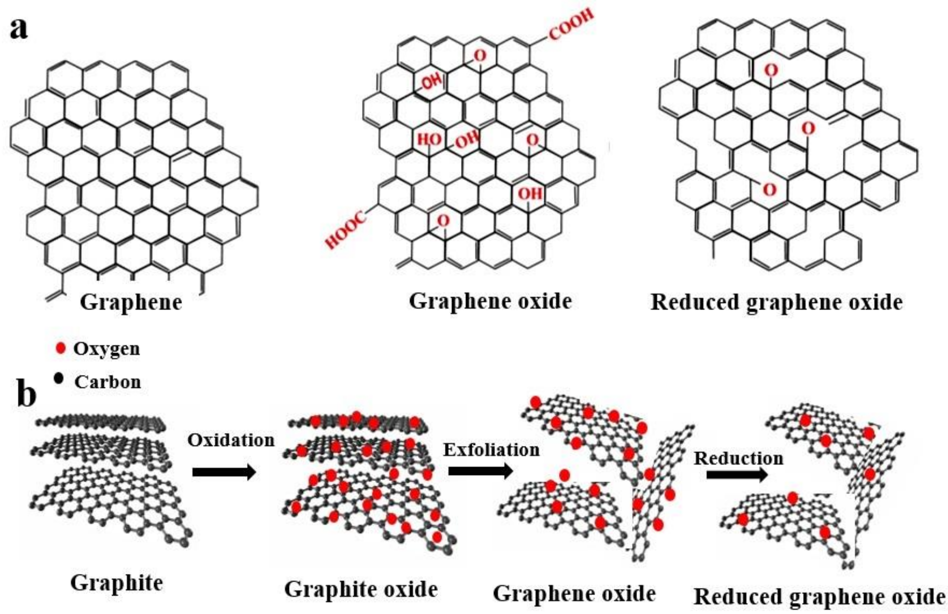

Figure 8. (a) Structure of graphene, GO, and rGO and (b) preparation methods of GO and rGO from graphite.

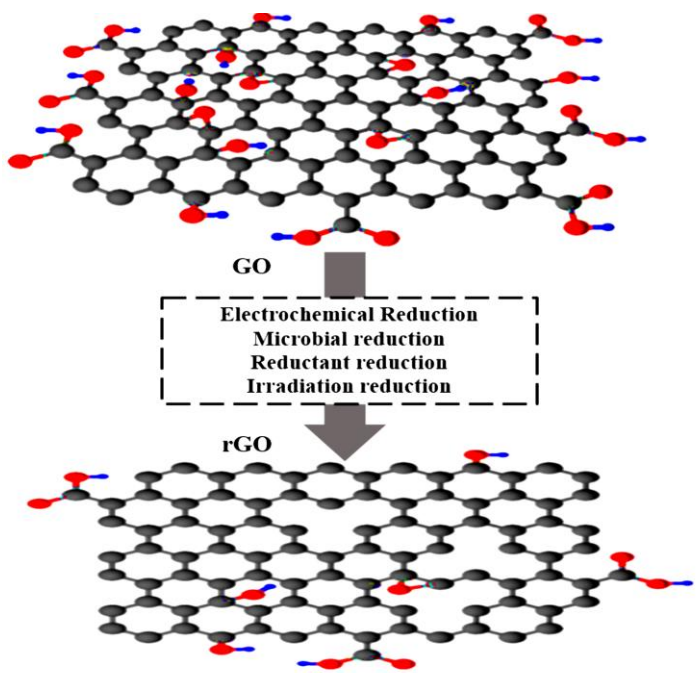

Figure 9. Conversion of GO to rGO.

Various works have prepared rGO by heating GO from 200°C to 700°C in an inert environment. Even though thermal reduction of GO is a popular method, it restricts the use of various desirable substrates and generates thermal stress (Huang et al. 2011). Other reduction processes are flashlight reduction, microwave reduction and electrochemical reduction.

Graphene/GO Sponge

Graphene with a structure similar to a sponge is called the graphene sponge. A three-dimensional graphene/GO sponge enables the diffusion of contaminants inside it. Thus, graphene/GO sponge is regarded as one of the most promising graphene-based adsorbents for practical use. The main challenge in preparing a graphene sponge is to maintain its porous structure and low mass density. The Lyophilization process can prepare graphene sponge and retain the porous structure even after drying of GO. Lyophilization is also adopted in preparing graphene sponges from graphene composites (F. Liu et al. 2012). In Lyophilization, an aqueous solution of GO is centrifuged for about six hours at a rotatory speed of about 1800 rpm to separate the precipitate. After that, samples are transferred to cold sources and freeze for about two hours until the suspension solidifies fully. Finally, the frozen sample is placed in a freeze dryer for 48 h in the presence of liquid nitrogen. A black cooler graphene sponge is prepared at the end of the process (X. Mi et al. 2012).

Researchers have attempted preparation of graphene sponge by the hydrothermal process; however, the porous structure of the rGO sponge is preserved by Lyophilisation only (Bi et al. 2012). The direct drying of the rGO sponge leads to the collapse of the porous structure. Attempts have been taken to develop alternative techniques where the supercritical CO_2 is used to preserve the porous structure (Sui et al. 2012). In this method, GO is suspended in an aqueous solution and reduced using vitamin C or hydrochloric acid. After that, the mixture is sonicated for a short while and heated for 12 h without mixing. Additionally, an attempt has been made to prepare 3-D structured graphene via solvothermal reaction of ethanol and sodium at 220°C (Choucair et al. 2012).

Functional Graphene

Graphenes are functionalised with various molecules to tailor and optimise their properties. Functionalisation of covalent groups is preferred as various pollutants interact with them strongly. Functional groups should be select carefully for the development of pollutant-specific adsorbents. EDTA functionalised GO is a suitable adsorbent for the removal of Pb^{2+} (Madadrang et al. 2012). Sulfonated graphenes have high adsorption sites and dispersibility in an aqueous solution (Y. Shen & Chen 2015). Therefore, various researchers have prepared sulfonated graphenes to remove aromatic pollutants such as naphthalene and 1-naphthol (Zhao, Jiang, et al. 2011). Yang et al. have designed the cysteine-rich metal binding protein (cyanobacterium metallothionein) functionalised GO (GO-SmtA) for selective adsorption of cadmium (T. Yang et al. 2012). Cetyltrimethylammonium bromide (CTAB) modified graphene (CTAB-GN) was used for the purification of hexagonal chromium from an aqueous solution (Y. Wu et al. 2013). CTAB-GN was prepared by dispersion of GO in CTAB solution. High-performance Pb^{2+} adsorbent was synthesised in one step method using tea polyphenols as reductant and functionalisation reagents (Song et al. 2012).

Inorganic Graphene Composite

Inorganic constituents in graphene provide new properties to it. Among various inorganic composites, graphene-based magnetic composites (graphene-magnetic material) are studied extensively for wastewater purification as they can be separated easily by an external magnet (Ain et al. 2020). Generally, magnetic NPs are embedded in the graphene sheets via chemical bonds. EDC/NHS modified Fe_3O_4 nanoparticles are terminated with $–NH_2$ groups that react with the carboxylic groups present in the basal plane of GO (He et al. 2010). Also, the EDC/NHS functionalisation has been adopted to attach FeO_4 to GO surfaces (Yao et al. 2012). Chitosan (CS) has been used in the form of a linker to synthesise composites of CS-Fe_3O_4 and GO (Fan, Luo, Li, et al. 2012). Also, CS-Fe_3O_4 NPs have been linked to GO by amide bonds through EDC/NHS functionalisation (Fan et al. 2013). GO is treated with thionyl chloride ($SOCl_2$) to prepare intermediate product GOCl, which contains plenty of acid chloride groups. After that, the Fe_3O_4 NPs are attached to the GO surface by the chemical reaction between acid chloride groups and amino groups (Xie et al. 2012).

The other synthesis strategy of graphene-magnetic composites is to grow magnetic NPs on the surface of graphene (Namvari & Namazi 2016). In this approach, researchers have prepared rGO–Fe_3O_4 hybrid by continuous starring GO, $FeCl_3·6H_2O$ and $FeCl_2·4H_2O$ in NH_4OH aqueous solution. The ratio of rGO and Fe_3O_4 is tuned by changing the concentration of GO solution (Geng et al. 2012; Qi et al. 2016). Recently, solvothermal methods have achieved popularity in the in-situ deposition of Fe_3O_4 (H. Sun et al. 2011; Q. Wu et al. 2013; J. Guo et al. 2012). Also, researchers have prepared magnetic graphene nanocomposites (MGNCs) by thermal decomposition of $Fe(CO)_5$ in graphene suspended DMF solution at 153°C (Zhu et al. 2012). GO-FeOH was obtained through precipitation of ferric hydroxide on GO (K. Zhang et al. 2010).

Apart from graphene-magnetic composite, graphene composites have been prepared with various other inorganic materials. The graphene-SiO_2 composites can be synthesised by the hydrolysis of tetramethyl orthosilicate (TEOS) in GO solution (Hao et al. 2012). Various works have demonstrated the preparation of graphene-MnO_2 by microwave irradiation of $KMnO_4$ (Y. Ren et al. 2012). rGO-$Mg(OH)_2$ was prepared by the precipitation of $Mg(OH)_2$ on GO, and subsequent reduction of solution using N_2H_4 (B. Li et al. 2011).

Researchers have found that GO coating on the traditional adsorbents such as sand, charcoal and activated carbon enhances their performance in water purification (W. Gao et al. 2011). GO coated sand was prepared by mixing clean sand in GO aqueous solution and heating the mixture at 150°C inside a vacuum oven. This coating process was repeated several times to increasing the GO-coating thickness on the sand. Additionally, Chitosan-rGO-composites coated sands have been prepared to purify wastewater (X. Li et al. 2019). In this process, rGO is mixed with metal ion precursors (H_2PtCl_6, $HAuCl_4$, $AgNO_3$, $PdCl_2$, $KMnO_4$) to prepare rGO-inorganic composites. After that, chitosan solution and rGO-inorganic composites were mixed with equal amounts of river sand as a supporting medium to prepare Chitosan-rGO composites coated sand. Graphene coated biochar has been used as another alternative for water purification (M. Zhang et al. 2012). Figure 10 shows an overall view of different graphene-based nanocomposite materials with their corresponding functional groups for the removal of multi pollutants such as organic, inorganic and pathogen from water bodies (Yap et al. 2021).

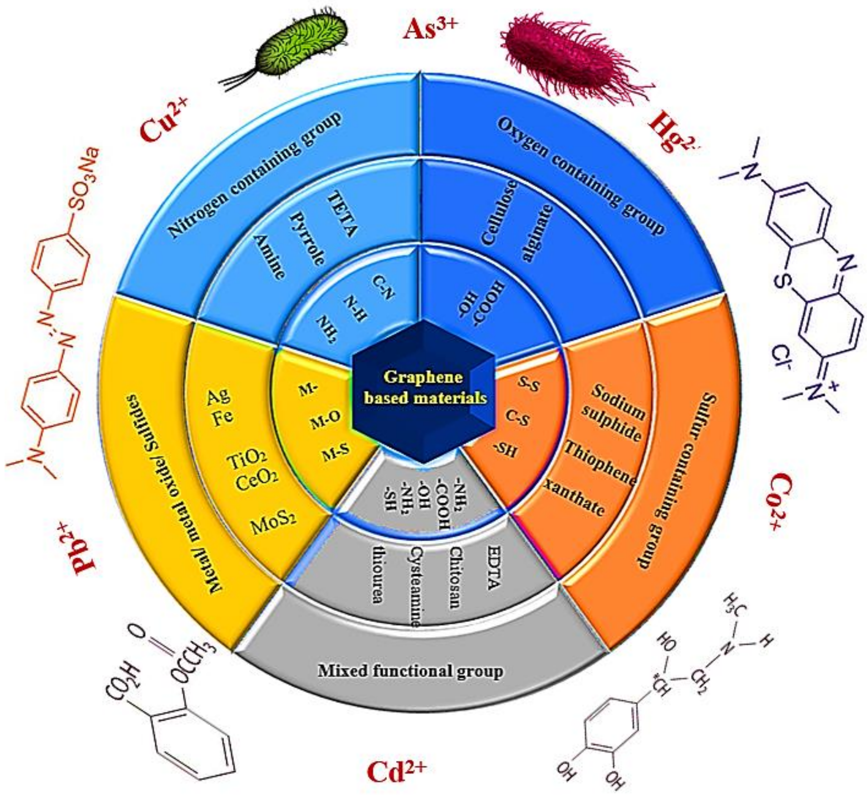

Figure 10. Overview of various graphene-based nanocomposite materials for water treatment.

CHALLENGES AND PROSPECTS

Immense progress has been made in the advancement of graphene-based materials; however, these materials are in the early stage to address the need for commercial products. Numerous factors hinder the commercial adoption of graphene-based materials, such as their limited availability and affordability. Another essential factor that should be considered is the simplicity of the shipping and storage area for these adsorbents. Dealings with wet (as a water-suspension) or dry (nanoplatelets) graphene/GO during manufacturing and storage involve high expense and complexity. GO storage in the suspended state is steady; however, storing a diluted GO dispersion is challenging and not economical. Above mentioned challenges could be overcome by transforming GO as a dried film or a composite material (Zurutuza & Marinelli 2014).

The aggregation of graphene flakes in an aqueous solution reduces the surface accessibility to pollutants. Hence, aggregation is a crucial technical issue in wastewater treatment using graphene. Graphene-based materials need to be modified with diverse functional groups to eliminate this technical obstruction (Bussy et al. 2013).

Graphene-based nanomaterial could cause contamination in water; therefore, continuous purification of graphene and its derivatives is essential during filtration. Magnetic particles modified graphene can be an alternative to eliminate self-contamination.

Since the large-scale productions of graphene, GO, and rGO are challenging tasks; hence, researchers need to find robust, simple, and efficient preparation strategies for those materials. Researchers have discovered various properties and applications of graphene in the last decade. However, further understanding of graphene-based materials demands thorough studies on the design, arrangement, size, practicality, reproducibility and properties. In summary, graphene-based materials have several disadvantages and advantages in water treatment. At the same time, graphene-derivatives have the potential to be star materials in water treatment in the long run.

Acknowledgments

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Chapter 13

CIRCULAR CITIES: CHALLENGES IN ADAPTATION OF NEW WASTE MANAGEMENT STRATEGIES

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ABSTRACT

On the planet where consumption is increasing day by day, limited resources are compelling to build a sustainable future. According to the estimations of United Nations, life in cities will be more common, with 66% of the population residing in cities, and the global footprint will triple by 2050. These statistics indicate that there will be an enormous resource shortage if no action is taken for waste recycle/recovery/reuse in cities. Moreover, results of over-consumption such as climate change are leading to precautions for food-water resilient cities. Due to these concerns, UNEP called countries for taking actions to reach sustainable development goals which were announced in 2015. The concept of circular city came to the agenda of countries for taking necessary actions. Regular (traditional) cities have linear flow of material and energy except for special efforts in local areas or in industrial sites whereas circular cities are developed in the context of circular flow of material and energy in city borders including urban regions to provide sustainable development. In circular cities, waste and wastewater is valorized and water, energy, and, materials (bioplastics, fertilizers, metal, protein-based food, building materials) are recovered from the waste and wastewater stream with appropriate technology choices. Therefore, waste management strategies requires to be adopted to this new concept of circular city. There are a number of technical, environmental, economic, human resources, social and regulatory challenges in ensuring the adaptation, and hence, the sustainability of waste management in circular cities. Inadequate and outdated infrastructure constitues a major obstacle to the application of sustainable technologies. Technically, a challenge circular cities face is that the all work accomplished still remains pilot or lab-scale. Sustainability of the market value of the recovered product demands more parameters such as processing, distribution and demand for the product after recovery. New technologies will bring new business areas and

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therefore qualified manpower will be required. It may take time for society to accept and adapt to change. This chapter aims to review potential challenges in adaptation of new waste management strategies through the transition period from linear cities to circular cities.

1. Introduction

Water, energy, raw material and food supply are the top listed problems in the future of the world. These limited resources are further endangered by global environmental problems such as climate change. Cities, where more than half of the world's population lives, are responsible for 60-80% of energy consumption and have a significant contribution to combating climate change as they cause more than 70% of greenhouse gas emissions (UN, 2016). Rapid population growth has increased the demand for water resources. In the world, approximately 30% of the total population does not have access to safe water now. According to the estimates, nearly half of the world population will not have access to water resources by 2030 due to irregular precipitation and sudden climate changes (Worldbank, 2021). This situation leads to immigration and causes both an increase in agricultural production and an increase in emergence of water demand. Increasing water and food demand are pushing cities towards reuse, recycling and recovery strategies. Increasing population and consumption rate and the tangible consequences of environmental problems brought people out to search for solutions. In the last decade, waste/wastewater was seen as disposable and only treatment technologies were focused on to remove the pollutants. However, water, energy, bioplastics, fertilizer, metal, protein-based food, building materials and many other consumer products can be recovered/recycled or reused from the waste/wastewater stream with appropriate treatment technology used (Chand Malav et al. 2020). These treatment technologies can be conventional ones or they could be developed on purpose for recovery/reuse/recycle. For example, microbial fuel cell technology is developed to apply both TOC removal and energy recovery (Shen et al. 2019). On the other hand, technologies such as incineration, pyrolysis, gasification, anaerobic digestion are conventional treatment technologies and, now, they, are called as Waste to Energy (WtE) technologies. Energy is obtained by using WtE technologies from wastes such as crop residues, livestock waste, paper and pulp, dirty oil or synthetic oil, as well as food waste, food packaging and compost (Chand Malav et al. 2020).

Today, about 3.9 billion people live in cities, but it is assumed that this number will exceed 6 billion by 2050. This growth has brought many problems related to the administration of cities, interconnected and complex, such as access to education, health, housing, infrastructure and other services. It is observed that especially developing countries are more affected by these deprivations, problems, financial difficulties and institutional deficiencies (UN, 2021). In this respect, potential conflict areas between economic growth and environmental sustainability stand out among the main problems to be addressed in order to ensure sustainability in cities. It is seen that concrete steps have been taken to ensure sustainability in cities. The Rio Conference, held in 1972, was the first conference where sustainability and sustainable development concepts were discussed extensively. Rio agreement comprises the sustainable development goals prepared to improve the social, economic and environmental quality of human settlement (UN, 2021). United Nations Framework Convention on Climate Change was approved in Paris. According to this agreement signed in 2015, countries will put the sectors such as energy, industry, agriculture, waste and electricity into revision. After these agreements, the concept of zero waste and circular cities started to come to the agenda.

It is expected that the processes such as recycling, reuse and recovery should be applied together in passing to circular city. In order to get an efficient system, it is necessary to carefully determine the collection, processing, conversion or recovery steps of all kinds of waste streams such as water, sludge, flue gas and solid waste. The outputs give substantial results in the processes where the management is done properly.

Field and literature studies on circular city implementations show that linear cities have obstacles to overcome for sustainable adaptation of waste/wastewater management. Technical, environmental, economic, socio-cultural, and regulatory difficulties make decision and implementation processes of recovery strategies demanding in terms of various aspects. This chapter examines the potential challenges that cities may face during the adaptation of waste/wastewater management strategies to circular city concept. Technical challenges include the properties of existing infrastructures, as well as, developing, optimizing and up-scaling of recovery/recycle/reuse technologies for waste/wastewater. The infrastructure systems of old and settled cities create an obstacle for innovative and practical systems that will be required for recovery technologies. In addition, since most of the recently developed technologies for nutrient and energy recovery remain pilot-scale, up-scaling of the systems is still uncertain. The need for pre-treatment of some technologies and uncertainty about performance and longevity are factors that limit the application. Lack of knowledge and improper design will also lead to unfavorable consequences in the project development process and optimization of the recovery technologies for the high-quality recovered product and sustainable technology will be a challenge.

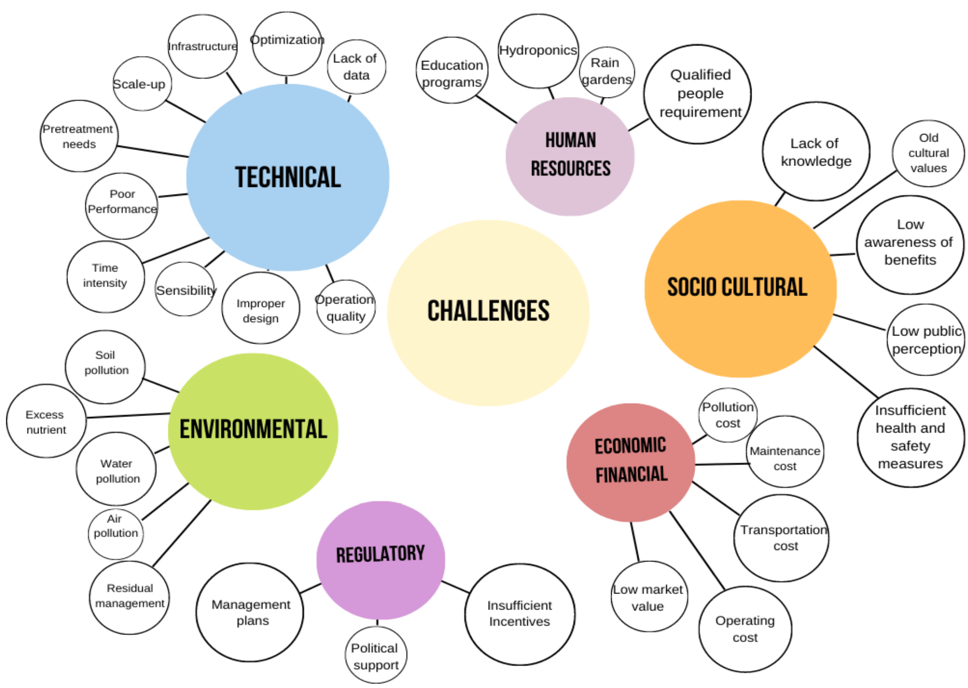

Figure 1. Main challenges in adaptation of new waste management strategies.

New recovery technologies may have adverse effects on the environment during the production or the usage of recovered product. Pollutant emissions sourcing from the recovery technologies may pose a threat for the environment. Also, the impurity of the recovered product, might create a contamination for the application area.

Probably, the most important point for decision makers and stakeholders in technology selection is the economic and financial status of the system. In addition, to the high initial investment and operating costs, the inability to find a market for the recovered product can be the major economic constraints.

From a socio-cultural perspective, people's positive perspective on recovered products and their willingness to use them are essential. It is not yet fully understood how the beneficial use of recovered products in agriculture, such as fertilizer, nutrient or irrigation water, will make a return to the society in terms of health. New technologies will bring new oppurtunities for the jobs such as engineers, architects, urban planners, economists and sociologists. While this situation provides employment, on the other hand, it will require more training programs and implementation process to train qualified person. More efforts are needed to expand practices that support circular cities, such as rain gardens and hydroponic farming.

Overall, recovery strategies and technologies are being implemented in most countries. There are some limitations to be considered in line with the sustainability goals, overcoming these obstacles depends on the strategies and willingness of countries. Figure 1 depicts the problems that circular cities may encounter in their circularity goals and waste management process. Sustainable cities can be reached with the cooperative work and harmony of the state, investors, public, civil society and all stakeholders. This process requires strict regulations and hard work, yet it will yield profitable outcomes even if it takes time.

2. TECHNICAL CHALLENGES

The choice of technology is fundamental in turning waste into a resource. However, the process of preparing existing technologies for new technology is troublesome. It depends on technology and many parameters such as reliability, robustness, flexibility and redundancy and their optimization (Puyol et al. 2017; Voulvoulis 2018; Kakwani and Kalbar 2020). Although cities and countries are willing to adopt resource recovery strategies, technical difficulties pose an obstacle to the implementation and adaptation of circular cities. The technical challenges are related to old and improper infrastructure, scale-up, pretreatment needs, poor performance, improper design, optimization, time intensity, sensibility, operation quality, uncertainty about longevity and performance, lack of data. Technical challenges are summarized in Figure 2.

2.1. Infrastructure

With the increasing population and industrialization, the need for infrastructure systems increases and linearization continues to spread through with the new infrastructure. Infrastructure systems that known as critical assets of cities create new challenges in their integration with circular cities. Infrastructure challenges may occur in building, local area (streets, provinces, etc.) and industrial scale.

Infrastructure on building scale is needed for the segregation of waste/wastewater at source that can provide efficient recoveries with the specified technologies for the target group. Wastewater can be collected separately as gray water, yellow and black water in homes, schools, hotels and businesses. Gray water is a valuable water source for irrigation in arid regions. Gray water, on the other hand, contains much less nitrogen than black water. 90% of nitrogen in waste water comes from black water thus, nutrient recovery is only possible from black water (Todt, Heistad, and Jenssen 2015). Buildings need to completely change their infrastructure systems to recover nutrients and energy from black water. Vacuum flushing toilets are suitable for energy production as they can collect black water separately. On the other hand, there are several challenges that make the application of vacuum toilets difficult. Initial investment costs are often high and a continuous energy supplier is needed for vacuum station and connecting lines to be close to buildings. Apart from that, bulky objects will damage the system as they can block the line (Jet vacuum toilet systems manual, 2021). Gray water can also be used as flushing water (Mehlhart et al. 2005). Rainwater can be collected separately or if mixed with gray water, it can be used in car washing and urban landscaping applications (Germer 2009). Separate collection areas and piping system will be reflected in the cities as a cost. Labeling and hanging an information form on the valves of the recycled water to prevent possible dangers are also an additional infrastructure duty. It will take time to change and reshape the infrastructure systems of the buildings. New pipeline to homes and businesses will be required for separate collection systems.

Considering all of this, it is necessary to encourage the use of separate toilets and to adapt the appropriate installation and infrastructure system for the buildings. Municipalities are the greatest supporters for fundamental transformation and development of cities. However, investors who do not want to take risks usually do not volunteer to implement recovery strategies. In addition to municipalities, contractors and those in the real estate sector have a large share in the radical infrastructure changes in buildings. The design and operation of the buildings to be built according to a new order requires great dedication from design to construction. In addition, expert real estate consultants are needed to facilitate public acceptance of these buildings. Apart from wastewater, the separate collection of solid wastes also diversifies the end use areas of wastes. Especially packages and metal wastes can be recycled sustainably and economically with the deposit-refund system. However, the possibility of contamination of incoming waste may require pre-treatment of the waste. Proper infrastructures in the buildings for separate waste collection should be adopted in order to get efficient results in waste recovery.

On municipality level, collecting the segregated waste stream is critical to separate the waste based on the recovery potential. Accurate collection of wastewater is necessary in cities, including the buildings because the separate collection of wastewater can be required for high recovery rates and feasible operations. In addition to the development of proper infrastructure in building scale, waste management strategies by municipalities and government with waste management is very important in transforming waste into products. Municipalities and government are responsible with developing proper infrastructure for the collection, transportation and treatment of waste and wastewater streams in the local scale. Wastewater collection requires the segregate sewer systems in order to sustain the proper quality of wastewater that provides great recovery rates and high product quality. For example, the segregation of rain water and domestic wastewater is the oldest application for keeping the water quality of rain water which is much less polluted than domestic wastewater. However, the concept of circular city will require even more complicated of segregations such as the separation of gray water, yellow water and brown water at the source and transporting to the wastewater treatment plants in segregated sewage streams. With wastewater separation, the amount of wastewater delivered to the sewer is reduced. Also, the volume of costly treatment systems decreases and investment costs are reduced. Gray water also causes a decrease in network water distribution costs as recovery systems reduce drinking water usage rates.

The other major challenge on the municipality level, is the up-grading of the infrastructure of municipal wastewater treatment plants' infrastructure to more efficient and feasible recovery technologies. For solid waste management, recycling/recover/reuse collection stations, transportation of solid waste from buildings to collection stations and then to the facilities and the infrastructure for the recycling/recover/reuse facilities are the major challenges. Optimization of the locations for collection stations between buildings and recovery facilities are very critical in terms of a sustainable waste management. Also, new infrastructures in the local scale may be needed for the recovery technologies.

Industries are responsible for the collection, treatment and management of the waste they generate within their site. For example, they are responsible for complying with the discharge standard determined by the municipality, for separating the solid wastes at their source and for securing their management. Sustainable and controllable system can be established as a result of the government's audits. Industries can contribute to circularity by adapting their infrastructure systems. Textile sector where there is intense water consumption in production, the need for water resources can be reduced with water recovery technologies (Mahto et al. 2021). An industry's waste may contain the raw material of another industry. It provides benefits for both organizations with recycling, reuse and recovery activities. This situation should be supported by the state and other stakeholders. Apart from recyclable and organic wastes, precious metals can also be recovered from waste/wastewater (Castro et al. 2019; Trinh et al. 2020). Flue gas generated as a result of industrial activities can be collected and processed separately. Separate collection methods are applied to prevent greenhouse gas emissions of waste gases from industrial facilities and solid waste disposal facilities. Separation and stabilization of the flue gas is also necessary in terms of preventing health problems. Many economic and regulatory challenges must be overcome for implementation.

2.1.1. Wastewater Segregation and Collection

Separating the wastewater stream at the right time and place facilitates resource recovery. It is known that the wastewater infrastructure system for recovery technologies has changed and developed recently. However, the fact that the infrastructure system design is only technology-oriented causes the environmental benefits to be ignored (X. Wang et al. 2018). This situation reduces the applicability of processes such as wastewater collection and recycling applications as a whole. Water, energy and nutrient recovery is possible from the wastewater stream. In order to obtain energy, nutrients and valuable products from wastewater, separation of the wastewater streams in the most accurate way is needed to have high quality end product and feasible operations.

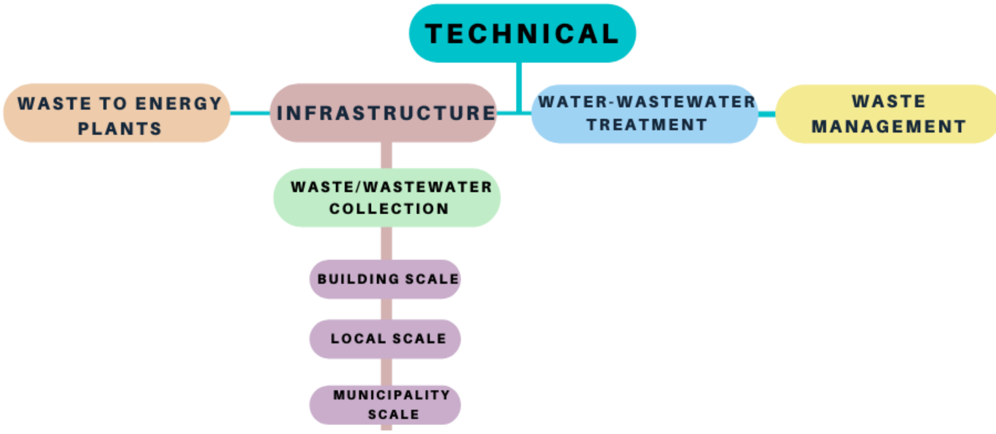

Figure 2. Technical challenges in adaptation of new waste management strategies.

Wastewater can be collected separately as gray water, yellow water, brown water and black water which is called Ecological Sanitation (ECOSAN). ECOSAN system does not consider wastewater as a waste; it aims to use each wastewater stream for different purposes, such as the use of wastewater as irrigation water, service water, fertilizer, compost and energy source (Beler-Baykal 2015). However, segregating domestic wastewater requires a serious infrastructure system in the building and local scale. With separate collection, the purpose is to use the correct pre-treatments for material recovery from separate water streams and send the wastewater to the ultimate process. For example, compost toilets are made available for this purpose. Compost toilets, also known as dry toilets, are used in many countries. Increasing drought and nutritional needs for agriculture increase the demand for composting toilets. On the other hand, the lack of studies for these sanitation systems makes applications difficult. There are many types of dry toilets which vary according to the needs and the region to be applied. Systems that get their energy from the sun or electricity can be decentralized or centralized. Electrical ones are generally used for buildings, while solar powered are suitable for outdoor park toilets (Aburto-Medina et al. 2020). One type of compost toilet is the worm type which can applied on small scale because keeping tons of worms together is not a sustainable practice. Composting projects are supported in Turkey because of the barren lands of Anatolia (Recycling Economy, 2019). There are some parameters that affect compost. These are carbon/nitrogen ratio, aeration, pH, temperature, particle size and porosity, and moisture content (Aburto-Medina et al. 2020). On the other hand, many problems may be encountered in practice. Conventional toilets must be broken down and new toilets must be installed in houses that are already inhabited, new pipelines must be laid. These actions may require an advanced infrastructure system, as well as building materials. Composting also generate reaction toby the public due to the possibility of blockage and odor (Diaz-Elsayed et al. 2019).

Urine separation, gray water collection and vacuum systems have begun to be implemented in cities and aim at environmental and economic sustainability. It is important that wastewater from cities is collected with a suitable sewer system. If the accurate strategies are not implemented, not only will the recovery from wastewater become difficult but also wastewater treatment will be harder. In cities with small settlements, a cluster system is recommended for the collection of wastewater. For the correct management and disposal of wastewater, all wastewater producers must be identified and the wastewater must be transported with appropriate units (Engin and Demir 2006). The innovations offered by the private sector to the infrastructure systems of the cities are discussed. However, the innovative transformation of recovery practices can be seen in cities with a structure where both the private sector and the state work together. Established and outdated infrastructure systems in cities pose an obstacle to municipalities responsible for separate transport of wastewater in sewer systems.

Rain water is a valuable water source in cities where it can be collected separately and treated accordingly for a specific beneficial usage. Moreover, increasing impermeable layers in cities cause storm water to create adverse impacts. Rain gardens, which are known as sustainable drainage systems, eliminate the negative effects of surface flow in cities and are candidates of being fundamental components of circular cities. Rain gardens have been implemented both on a small and large scale in Norway efficiently. This project is planned to be implemented in different countries, as well. The difficulties of the process are that it requires continuous monitoring and planning and problems can arise during the design phase due to lack of information (Venvik and Boogaard 2020). In another study, it is mentioned that it is possible to both control runoff and prevent pollution with sustainable infrastructure systems. Swales are one of the water strategies. These ditches contribute to the increase of the groundwater level through infiltrating more rainfall into the underground, the increase in biodiversity, the reduction of the need for irrigation water, the prevention of erosion by decreasing the runoff velocity, and the increase of the driving safety on the road surface by collecting the rainwater in the road pavement (Sharma and Malaviya 2021). Swales are designed as wet and dry, and each has different advantages and disadvantages (Of et al. 2017). Constructed wetlands, filter strip, green roofs, riparian buffer zone, wet storm water pond and raingardens are other applications of green infrastructures (Sharma and Malaviya 2021). It is aimed to make these methods applied for rainwater management widespread. Extensive usage depends on overcoming the challenges of the money and regulations that cities have to devote to their development strategy.

2.1.2. Waste Segregation and Collection

Solid waste management refers to a process that includes many components such as the generation, collection, storage, transfer, processing control and disposal of solid wastes and material recovery. Wastes produced in cities are classified as recyclable wastes, organic wastes, hazardous wastes and other wastes. Circular cities will be segregating all of these streams for the recovery.

On building scale, the proper use of land in circular cities is encouraged to overcome the challenges of waste segregation. In addition to land use, old dated infrastructure in buildings, insufficient technical equipment, and lack of awareness of the public about the separation methods and the lack of regulations decelerate the practices (W. jing Wang and You 2021). All of these challenges should be faced in order to make efficient waste segregation on building scale in circular cities. For example, the recovery of precious metals from discarded e-wastes are an obstacle due to incomplete infrastructure systems. The inadequate infrastructure of the buildings with the strategies that are not suitable for e-waste collection and disposal makes it difficult to recover electronic waste in cities (Eneh, 2021). New generation of buildings in the circular cities should have proper segregation areas for each waste stream.

On municipality level, the burden of the cities is reduced in the system where recyclable wastes, organic and mixed wastes are collected separately. Waste collection will be one of the fundamental components of circular cities since each waste stream will be recycled. According to research, there is no city that segregate waste 100 percent at the source and it is expected to be challenge for circular cities (Chand Malav et al. 2020). Waste segregation challenges include the optimization of the routes for the collection of solid wastes since there will be a number of streams that needs to be transported separately. Optimization of the road map of the collection vehicle, the volume of the vehicle, the collection periods, labor cost, maintenance cost and pollution emissions will be necessary (Rathore and Sarmah 2019). For example, one study found that setting up a transfer station speeds up the garbage collection process and reduces air pollution while benefiting economically. After the improvement of this infrastructure challenge, city has reduced the greenhouse gas emissions in a year by 445 tons. Substantial results depend on expert opinion and public surveys. Improvement efforts will provide financial, environmental and economic benefits to the states in addition to the infrastructural benefits (Abdelli et al. 2016).

Regarding waste collection, although it may seem simple, it is a prominent problem in low-income countries for vehicles to collect waste efficiently from waste points. Due to the narrow and unpaved road, waste collection vehicles cannot fulfill their duty. Slumps are unavoidable in low-income countries. While considering recovery strategies, these neighborhoods should be modernized with urban transformation.

In industrial scale, life cycle analysis highlights the importance of implementing integrated solid waste management for product recovery in large-scale industrial facilities. In industrial plants, practices such as reuse or recycling of materials should be encouraged to increase the efficiency of circular city implementation (Duić, Urbaniec, and Huisingh 2015). Waste from industrial activities varies according to the sector. The company itself is responsible for the disposal of industrial waste from the production stage. According to the polluter pays principle, industries are encouraged to reduce their waste. In this way, the waste is transformed within the loop. The biggest challenge is the heterogenization of waste by mixing industrial wastes with domestic wastes (Awuchi, Chinaza Godswill 2020). This eliminates the options of waste such as recovery, recycling and reuse. In circular city implementations, industries may be asked to update their infrastructure for the efficient waste segregation within the facility and be promoted for the collaboration of waste recovery with municipality.

2.2. Waste to Energy Plants

Circular cities are planned to include waste to energy plants for the recovery of waste as energy. Pyrolysis, gasification, and liquefaction are thermal whereas, anaerobic digestion, and composting are the biological technologies frequently applied in energy recovery from waste. Apart from wastewater flow, waste to energy processes play a major role while converting waste to valuable products. Waste heat is an issue that needs to be dealt with in energy recovery with WtE technologies (Nanda and Berruti 2021).

The most crucial step to obtain energy from used and discarded wastes is the correct separation of the wastes at the source and the correct management. Therefore, it depends on the management strategy of the region (Tun et al. 2020). Characteristics of the waste determines the quality of the recovered product. The recovery technology may show poor performance due to reasons such as incorrect separation of waste or the waste not having an appropriate calorific value due to lack of pretreatment. For example, the incineration method used by most developing countries for energy generation has failed due to the high moisture content of the waste (Yong et al. 2019). In this case, pretreatment such as dewatering technologies are needed. The mechanical dewatering unit used to dewater the excess sludge from the wastewater can reduce the moisture content of the sludge up to a certain rate. As the moisture content of the sludge increases, the energy efficiency to be obtained from the sludge will decrease (Kehrein et al. 2020). In such cases, optimization strategies for the pretreatment should be developed to keep the moisture content of the sludge feeding the system both low and stable. If the existing incineration processes cannot be applied due to improper design, recovery technology and process should be designed and developed depending on sludge properties. The quality and quantity of waste can be affected by human as well as by climate and seasonal changes. In Southeast Asia pre-treatments such as drying operations are applied in the process of obtaining energy from waste during rainy seasons. Nevertheless, pre-treatment applications are seen as time-consuming in recovery processes (Tun et al. 2020).

Bio-oil, char or gases can generally be obtained from solid wastes through pyrolysis method. The quality of the products obtained varies depending on many factors which must be controlled for the system to work efficiently. The moisture content of the solid wastes, the temperature of the environment, the heating rate of the process, the steam residence time, the inert gas flow rate and even the design geometry of the reactor affect the operation of the system. Pyrolysis can be classified as slow, medium speed and flash pyrolysis (Nanda and Berruti 2021). Since the diversification according to the ambient temperature and the recovered product will provide a wide choice in determining the recovery strategies, pilot studies should be conducted to determine the recovery strategies specific to the situation. The process should be designed and operated according to the amount of waste to be loaded into the system and its characteristics. Incorrect design brings a difficult optimization process. Besides its high capital cost, continuous energy input to the system brings about the operating cost extremely high. Technically, it involves complex reaction processes. Requires drying process for high moisture content of sludge. In addition, studies on this subject are at the beginning stage (Oladejo et al. 2019). More studies and literature information are needed for the pyrolysis method. The safe disposal process of char, management of air pollutants, economical efficient system and qualitative product should be developed.

The gasification method is used to produce syngas from carbon-based organic materials, and also can produces hydrogen gas, which is classified as clean gas (Nanda and Berruti 2021). One of the main challenges of gasification is the pretreatment need to increase the quality of recovered material. Since the moisture content of the waste is very important, a large budget is allocated for the drying process. In addition, catalysts that accelerate the process and increase the purity of the recovered product are examined in the profit-loss analysis as they increase the operating cost.

Lack of studies on liquefaction which is a thermochemical energy recovery technology create uncertainty for decision makers. The waste gas and high ash content emerging after the process requires an advanced treatment system. More studies are needed to demonstrate its technical applicability and to design a more sustainable system (Couto, Calijuri, and Assemany 2020). The difficulties in the thermal liquefaction method caused it not to be preferred over other WtE technologies. There are a number of technical and economic challenges while treating residual aqueous phase since it contains a high proportion of carbon, sulfur and nitrogen compounds. Since animal manure is generally used as waste, clogging may occur in the pipes and technical malfunctions may occur. The quality of the bio-oil depends on some aspects the nitrogen ratio of the waste and operation temperature. In addition, it is imperative to provide the necessary infrastructure system at the facility in order to reach and fix a certain temperature value in operational conditions (Khoshnevisan et al. 2021).

Anaerobic digester contains microbial metabolic reactions that take days and weeks for energy recovery. Therefore, it is considered time consuming (Nanda and Berruti 2021). Toxic and chemical substances such as xylene, ethylbenzene, oxygenated organics such as phenol, acetophenone, catechol, cresol, furan, hydroxymethyl furfural (HMF) and hydroxy acetaldehyde (HAA) that damage the working mechanism of microorganisms can enter the system (Seyedi, Venkiteshwaran, and Zitomer 2020). The aesthetic appearance of recovered technologies and the area they occupy within the facility are ignored by most investors. Due to the solid content of the bio solids between 1 and 5 percent, anaerobic digesters occupy big area in the facility (H. Wang et al. 2008). These challenges should be studied for a proper design and optimization of the operation that can suggest solutions.

Waste to energy systems can be precise and these technologies are prone to the effects sourcing from their complexity and stability. Therefore, these challenges should be studied to improve the full-scale implementation in the circular cities. Algae is involved in obtaining bioenergy from domestic and industrial wastewater streams. It is known that algae in the bio refinery concept are affected by heat and light transmittance (Chew et al. 2017). Therefore, these technologies pose challenges to apply in places exposed to low temperature and limited daylight. In addition to the quality of the products obtained from recovery technologies, the management of the resulting waste stream is important for the sustainability of the closed system. Sludge removal as in conventional wastewater treatment cannot be applied to sludge containing microalgae, which makes it tough. The sludge needs less chemicals and its algae biomass require an innovative sludge treatment strategy (Bhatia et al. 2021). In the bio refinery concept, the growth of microalgae is crucial to recover nutrients and valuable products from microalgae. Nutrients required for the growth of microalgae can be supplied from different wastewater streams. Choosing the right nutrient ratio will determine the dilution ratio of wastewater. This process requires serious precision and also, creates an extra cost (Chew et al. 2017). The biggest challenges of these systems is that, different technologies are integrated in the bio-refinery and each of them depends on the other one. Pilot scale applications for the efficient implementation of the refineries are required for the circular cities.

2.3. Water/Wastewater Treatment

In the applications of water, energy, nutrient and valuable product recovery from wastewater, it is aimed to move technologies to real scale rather than small scale. Therefore, the existing challenge for wastewater recovery is full scale implementations. In conventional wastewater treatment plants, biological activated sludge systems or advanced oxidation technologies are more common. However, these technologies are not optimized for the recovery. Wastewater recovery technologies either different from conventional ones or implementation of new technologies combined to conventional ones are needed. For example, it is possible to obtain a bio refinery concept with the dark fermentation method applied in hydrogen recovery from wastewater. However, large-scale hydrogen production requires fuel to be stored and transported over longer distances. While research is being done to bring this process to industrial scale, reaching real scale depends on critical challenges (Dahiya et al. 2021). As a result of not collecting waste streams separately, the efficiency of the system depends on pretreatment need. Separation, collection and pre-treatment of wastes are the major problems (Dahiya et al. 2021).

Microbial fuel cell technology is another resource recovery technique for wastewater recovery. Although it seems energy efficient and safely, there can be some deficiencies in system such as regular monitoring of enzyme activities for biological technologies(Nanda and Berruti 2021).

Although forward osmosis, a nutrient recovery technology from wastewater, promises real-scale studies with based on its lab and pilot-scale studies, more investigations are needed to overcome challenges for full scale implementations. For improving traditional wastewater treatment facilities and providing resource recovery, forward osmosis technology can be a sustainable solution. However, the different velocities of the water flow into the membrane and the water flow in the membrane is a problem that needs to be taken into account when scaling up this technology (Jafarinejad 2021). Reproducible results in laboratory and pilot-scale studies seems not to limit the application of membrane technologies, yet it is not enough to promote in their large-scale transfer. Nanomaterial coated membranes have been introduced to be applicable in real wastewater treatment plants for forward osmosis and reverse osmosis technologies that may be preferred by industries especially in recovery. As it is a new approach, more research should be done for large scale applications (Mahto et al. 2021). The use of nanotechnology in water and wastewater treatment is limited to lab and pilot scale. These nanoparticles, whose toxic effects and fate have not yet been determined, have a high probability of being released into the air, water and soil. There is concern about its use, as it has environmental and social risks (Kamali et al. 2019).

Within technical problems, the time-consuming process is considered a challenge in transition to circularity. For example, ammonia striping and precipitation methods, which are nutrient recovery methods from wastewater stream, are considered time-consuming due to many reasons such as pH adjustment and the effect of the process on common ions (Cao et al. 2019).

2.4. Waste Management

Waste management includes streams of glass, plastic, metal, food waste and wastewater sludge. In order to contribute to the circular economy, adjustments are made to the infrastructure systems of cities in order to collect, process and separate waste (Tallentire and Steubing 2020). It is important to recycle glass, metal, plastic material without losing their properties, in order to prevent re-production. Compared to wastewater recovery technologies, waste recovery for glass, plastics and, metal have already been applied for a while and are less complicated in terms of technology. Therefore, these technologies are not expected to be critical new challenges except for the high-capacity needs.

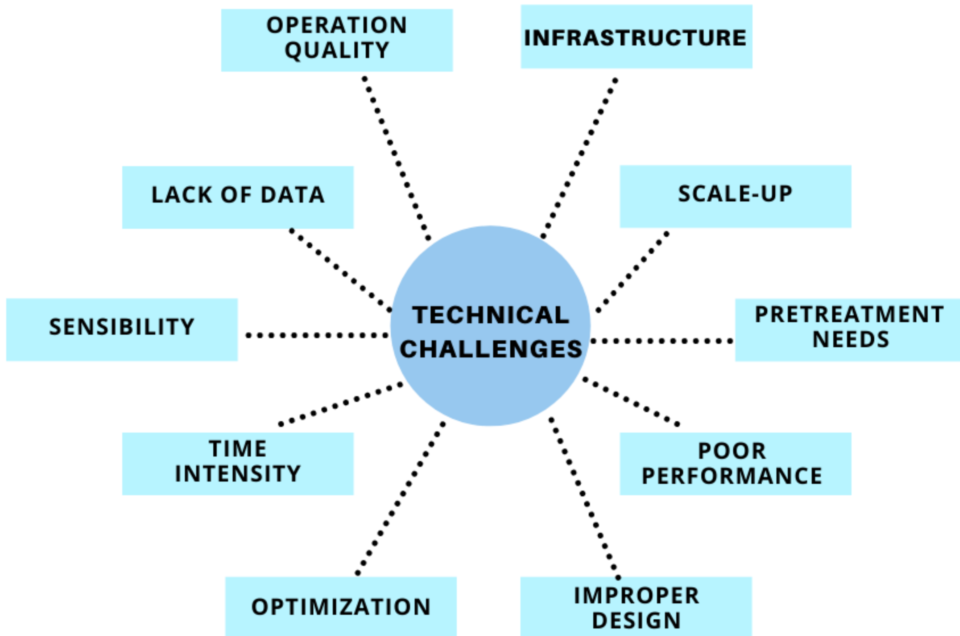

Figure 3. Summary technical challenges in circular cities.

Wastewater sludge can be primary, secondary, tertiary and chemical sludge. Energy, bioplastic, phosphorus, enzyme, protein, precious metal, and, syngas can be recovered from the wastewater sludge according to the characteristics of the sludge and the technology chosen (Gherghel, Teodosiu, and De Gisi 2019). Sludge with large volumes should be collected in a separate stream in treatment plants. The challenge is to optimize the physical, thermal, chemical and biological processes. Proper management of sludge with optimized process lowers the carbon footprint and reduces operational costs (Piao et al. 2016).

3. Environmental Challenges

Recovery technologies benefit the environment when considered together with environmental approaches.. Nvertheless, both recovered products and recovery technologies can have an environmental impact as well. The scarcity of the full-scale applications is an obstacle in understanding the accuracy of the available data on environmental impacts of recovery technologies. Although there are studies on the life cycle analysis of recovery technologies (Remy et al. 2016; Diaz-Elsayed et al. 2019), they are limited with laboratory scale or pilot scale.

3.1. Environmental Impact of Recovered Products

Usage of recovered products can lead to environmental impacts, as well. Environmental challenges of circular cities will be controlling or minimizing the environmental impacts of the recovered products. The usage of compost and biosolid as fertilizer and treated wastewater as irrigation water or drinking water can be the main challenges since recovered waste and wastewater have to be safe enough not to harm human health. Organic matter recovery by composting technique is common. Biological stability and maturity are the parameters that should be controlled during process (Cesaro et al. 2019). Otherwise, recovered product may have many negative environmental impacts on agricultural activities. Depending on the biological stability of fertilizer, soil structure, hydraulic properties and organic matter content, the soil's adaptation of the recovered product to its structure may vary. High salinity and sodium adsorption rate can also change the strategies in the application of the recovered product. Application of recovered product to soil can lead to pollution by changing the quality of water bodies. If it is assumed that the crops in the agricultural field can take nutrients in a certain capacity, the application excess amount can harm the quality of the plants. In addition, it has been proven that recovery products containing heavy metals cause toxicity on crops (Ofori et al. 2021). It is a great uncertainty that emerging pollutants are present in recovered water and these pollutants have not been included in regulations yet (Pan et al. 2019). Although there are some obstacles to the use of recovered water in agriculture, with advanced technologies and life cycle analysis, water can be used at the drinking water level (Pan et al. 2019).

Many countries like Singapore, China and Japan obtain drinking water from wastewater and use it as potable water or in industrial area. Using recovered water as drinking water is controlled by regulation since it includes pathogens (Singapore's National Water Agency, 2021). EU Guidelines for Bathing Water Regulation (76/160/EEC) contains some issues related with situations in case of ingestion of flushing water and contact with skin in a possible case (European Commission, 2012). In Turkey, according to Environmental Legislation Article 28 treated wastewater can be used under certain conditions as irrigation water. Recovered water parameters should be monitored according to Water Pollution Control Regulation (Mevzuat, 2021). However, in addition to conventional pollutant parameters, emerging pollutants in wastewater should also be taken into consideration and the relevant laws should be given priority.

The purpose of minimum liquid discharge and zero liquid discharge systems is to recycle clean water and reduce waste generation to zero. During fresh water recovery, mixed salts may occur in the concentrated wastewater section. Since concentrated water have the potential to leak into surface or groundwater, it poses a danger to natural life (Panagopoulos and Haralambous 2020). Nutrient recovered from wastewater causes both environmental and human toxicity in agricultural practices. The heavy metal in the nutrient is released into the soil and has a negative effect on living organisms (Fang et al. 2016). Although the ammonium stripping and struvite precipitation method yields a soluble nutrient for plants, the nutrient recovered by membrane technology must be pre-treated before use. In the soil where inappropriate nutrient application is applied, it causes a decrease in product quality and a risk for soil creatures.

3.2. Environmental Impacts of Recovery Technologies

Environmental impact of recovery technologies is determined according to some problems arising from the infrastructure of the facility, chemical consumption and energy use during the process. Products obtained from recovered technologies have various market values according to their quality. In this flow in a closed system, the waste stream generated as a result of the recovery technology should be handled specially. It is necessary to apply continuous monitoring from the construction of recovered technologies to their operation. Otherwise, inadequate monitoring during operation can lead to undesirable environmental problems.

Recovery technologies have to be analyzed in terms of environmental effects like conventional treatment processes in order to be sure about the safety of the operation. Although recovery technologies include promising, innovative and environmentally friendly approaches, sludge produced during bio methanation and anaerobic digester processes contains high amounts of heavy metals and pollutants (Chand Malav et al. 2020). Also in microbial fuel cell process waste is problem. Excess sludge production can block pipes and membranes (Nanda and Berruti 2021). Same situation is valid for the wastewater. It is possible to recover valuable products from wastewater. While recovering tungsten the inability to recycle aqueous solutions and chemical reagents at the last stage and the high salinity in wastewater indicate that waste management is a problem during recovery (Shen et al. 2019).

In addition to the recovered product, it is expected that the carbon footprint of the technology achieves close to zero. It is necessary to carry out preliminary studies as the variety and status of water resources may change according to the city, region and state. Knowing the water sources will prevent contamination of a possible surface and groundwater. It is obligatory to comply with the discharge limitation in addition to the quality of the recovered product. The heat used by the technologies in the process stage should be disposed of as waste heat afterwards. If the discharge point is a lake or river, it creates the danger of thermal pollution. Air pollution and greenhouse gas emissions are related to energy consumption. The more energy is consumed, the higher the greenhouse gas emission is generated. For example, it has been declared that air stripping and precipitation technologies produce 18 kg/eq-capita carbon dioxide per year (Kjerstadius et al. 2017). On the other hand, it is thought that the contribution of membrane technologies to air pollution will be less (Xie et al. 2015).

Even though it is thought to be less compared to traditional methods, the environmental damage caused by the recovered system should not be ignored. Challenges can be emission management and residual management if pollution is not properly managed.

4. Economic and Financial Challenges

Circular cities should be evaluated with cost benefit analysis in the consideration of circular economy. In this sense, the existence of economic constraints will prevent the transition to circularity. Many elements such as limited demand for the recovered product, low market value of new product, transportation cost, operating cost, maintenance cost and pollution cost create economic obstacles for sustainable circular cities.

Undoubtedly, the most common problem encountered during the application of recovery technologies is insufficient financial investments. Financial crises experienced by countries also pose an obstacle. Depending on the financial possibilities of the countries, the investment they can make in recovery technologies varies. For example, the El Prat wastewater treatment plant spends 14 million euros for new technologies, while the SantFeliu wastewater treatment plant spends 1.12 million euros (Lazurko 2018). Countries that have adopt resource recovery strategy before can make larger investments to improve it. For example, a budget of $ 5 billion has been allocated for infrastructure investment in the Australian state of Victoria by 2044. In addition, it has a budget of up to 167 million dollars not only for infrastructure but also for investment opportunities such as technology and expert needs (Sustainability, 2021).

Depending on where the recovered product will be used, transportation cost may arise. It can be financially challenging, and this may cause additional difficulties in processes such as distribution and transportation, depending on the infrastructure (Yi et al. 2011). In addition, separate collection of solid wastes creates additional transportation costs (Towa, Zeller, and Achten 2020). The high moisture content of the waste coming to the recovery unit will require drying process and will be reflected in expenses as an extra cost. While it is expected that the waste moisture content is low in energy recovery with thermal technologies. In bioenergy recovery with compost, it is supposed that the optimum moisture content of organic wastes should have 55 to 70% (Yeh et al. 2020).

The aim in circular cities is to provide maximum resource conversion by minimizing waste reduction. While this is possible with recovery technology, the disposal of the resulting waste stream requires special effort. Wastes with different characterizations produced by new technologies must be disposed of with certain procedures and new waste management strategies. Allocating a budget and training qualified people to implement these will be reflected in the expenses.

The biggest obstacle in bringing recyclable products to circularity is the market value of the recycled product. It is necessary to deal with many more parameters such as processing, distribution and demand for the product after recovery. For example, in order for the recovered phosphorus to be used in agriculture, phosphorus must be required in the area to be applied, otherwise detrimental consequences will occur (Diaz-Elsayed et al. 2019). The resource need in urban and rural areas varies. In rural areas where agricultural activities are intense, the need for nutrients is higher than in cities. In a study conducted in Spain, the struvite obtained by the REM-NUT® process is recovered 22.6 to 30.1 times more nutrients than demand. On the other hand, although the least struvite is gained with AirPrex®Methodology, it still gains more struvite than necessity (Rufí-Salís et al. 2020). While this is the case for the nutrient, the situation is different for water recovery. The agricultural water need of Western countries comes second after the need for industrial water consumption (Kehrein et al. 2020). The water streams coming to the wastewater treatment plant can be domestic water, industrial water and storm water. This considerable water need in the agricultural field can be met only half by the water recovered in the wastewater treatment plant (Kehrein et al. 2020).

The market value of the recovered product depends on social acceptance. This situation creates a risk for institutions that will make technological investments for recovered products such as water and phosphorus (Hall, Priestley, and Muster 2018). Market values of nutrients obtained from manure in animal farms are considered high (De Vrieze et al. 2019). On the other hand, it is the initial investment and repair cost that should be considered during the recovery phase. For example, it has been observed that the ammonium stripping process consumes 24 kWh of energy per ton of nutrient produced. In addition, the maintenance cost in a real-scale facility was determined as 0.10 euro per ton of nutrient produced. It was account that the total investment cost was 500 thousand euros. In addition to these expenses, the market values of recovered ammonium sulphate and struvite are 1 euro and 1.9 euro per kg, respectively (De Vrieze et al. 2019). The purity grade of the recovered product is of great importance in determining the market value. Compared to the equivalent products in the market, it is necessary to obtain the non-contaminated pure form of the product in order to contribute to circularity.

Biological recovery technologies from wastewater have been compared in a large-scale economic analysis. The electricity and nutrients obtained from wastewater could not gain as much as expected (Puyol et al. 2017). The current cheap electricity tariffs may have had a negative effect on the market value of the recovered product.

5. Human Resources

New technologies required for circular cities will bring new business areas and therefore qualified manpower will be a challenge to overcome. Providing fast, accurate and continuous education is a situation that makes it difficult in this sense. Education and research programs on recovery technologies are not developed, and there is a need for qualified people responsible for technical parts such as the installation, maintenance and operation of recovery technologies (Tun et al. 2020); Chand Malav et al. 2020). While advancing step by step in the technological age, the replacement of the labor force by the machine leads to a loss of some jobs. It may take time for society to accept and adapt to change.

The concerns of the cities, which were planned to be built from a linear land, was to take the garbage to the furthest point. Now, city planners and regional managers are deciding how a city can be built and managed in a circular manner in terms of waste management. For example, rain gardens, created by the collaboration of different disciplines such as city planners, architects and engineers, are preferred for sustainable water management, nowadays (Pan et al. 2019). The recovered water can be used for toilet flushing or garden irrigation in the buildings. Maybe, municipalities or residential mass houses will need special gardeners for the efficient operation of the rain gardens.

Human resources can be a serious problem in terms of new agricultural applications in the circular cities such as hydroponics in which the nutritional needs can be met in cold climates where water and sun are insufficient. With this manner, plants can be grown by using mineral nutrient solutions in water without using soil. Since there is no need for land, agriculture can also be done in areas with unproductive soil. However, there are some drawbacks of using this system. Macro and micronutrients needed by plants should be given in sufficient quantity. Technically, the measurement and control of parameters are limiting factors. In particular, farmers have great responsibility, government incentives are needed for the implementation and training of this method (Sambo et al. 2019). Since the operating costs are high, the plants produced are exported instead of being sold domestically (Popular Agriculture, 2021). Also, for the safe production of vegetables and fruits, physical and chemical disinfection methods are used in hydroponic systems (Nanda and Berruti 2021).

Table 1. Economic and financial challenges in adaptation of new waste management strategies

Cost Type	Economic and Financial Challenges
Investment Cost	Change 1.2 million euro to 14 million euro
	167 million dollars investment for infrastructure
	technology and expert needs
Transportation cost	Complications while distributing the product
Operational cost	Drying process requirement, different characteristics of wastes
	High energy and chemical consumptions
	24 kWh of energy per ton of nutrient produced
	Maintenance cost is 0.10 euro per ton nutrient recovered
Market value	Production higher than demand
	Depends on social acceptance
	Market values of recovered ammonium sulphate and struvite
	are 1 euro and 1.9 euro per kg,

6. SOCIAL-CULTURAL

In decision-making processes, the most outstanding point in sustainable development strategies is the people. Lack of knowledge, low awareness of the benefits, low public perception, insufficient health and safety measures, old cultural values are seen as difficulties in adapting circular cities from traditional cities.

Soil, water and air pollution, dust and odor, noise, increased traffic and visual impact, which occur due to improper environmental management, are considered as social driving forces. Imbalance in infrastructure systems can have a negative impact on citizens. In some cities, due to the lack of space, the establishment of technology close to the city causes aesthetic concerns. The NIMBY (not-in-my-backyard) syndrome is a well-known social concern (Tian and Chen 2015). Public confidence in circularity can be gained through responsible action of the local government and the state. The trust of the people can only be gained through the responsibilities and duties of the local authority.

Public health and concerns are not taken into account in the selection of recovery technologies. If WtE recovery technologies are not managed correctly, there may be harms direct or indirect effects on human health. Especially, the air pollutants generated during incineration, such as sulfur dioxide, nitrogen dioxide and furans, cause water and soil pollution due to the heavy metals in the fly ash. These pollutants are carcinogenic (Chand Malav et al. 2020). Trusting the government and its fairness are important for the social acceptance of recovery technologies (Mccrea et al. 2016).

A health risk study was carried out according to human risk and exposure estimates of all age groups in a region where WtE production facilities are located. In the study, all exposure modes such as inhalation, dermal contact, food intake was calculated. In addition, the routes of potential pollutants were considered using atmospheric dispersion models. Study has shown that long-term exposure poses a threat to human health (Metro Vancouver, 2014)

Waste collection systems may include curbside collection, drop-off collection, by back collection and deposit refund collection systems (Mwanza, Mbohwa, and Telukdarie 2018). During the collection of solid wastes, the aerosol and particulate matter that workers are exposed to from the wastes cause respiratory diseases (Akhtar et al. 2015). Workers are exposed to direct and indirect disease-causing situations. Bio aerosol and particulate matter are released from organic wastes and hazardous wastes. Also, waste contaminated with bacteria and fungi threaten human health in material recovery facilities where manual separation is carried out (Wikuats et al. 2020). In addition, wastes that are not separated regularly, broken glass fragments and wastes containing irritants cause harm to workers. Managements should regularly provide occupational health and safety and this should be followed.

In the local scale, the challenges for waste collection are diverse and can depend on mostly socio-economic status. In researches, the increase in the welfare of the societies causes people to generate more waste (Akhtar et al. 2015). The first problem local governments encounter in their waste-to-product strategies is the amount of waste. Most of the rapidly growing cities are forced to deal with an increased and sometimes uncontrollable waste amount .

Water scarcity has seriously affected several countries. In arid and semi-arid regions, wastewater is pre-treated and reused in agricultural activities. It is rather difficult for the public as well as the farmers to accept this phenomenon. The biggest risk for people are the presence of pathogens, organic and toxic substances that can arise due to the inadequate treatment of wastewater. It poses a danger not only for surface waters, but also for groundwater (Ofori et al. 2021). The number of water resources cannot be increased, but the need for water resources can be reduced by recycling water. Investments in water reuse and recovery should be given importance. The use of water in agriculture and in daily life creates some problems. Concerns about food safety and public health limit technologies that deliver drinking water from wastewater. Therefore, water characterization must be done and necessary regulations must be revealed. It is inevitable that clean water resources will be depleted day by day, thus it is aimed to inform and encourage the public on this issue (Ungureanu, Vlăduț, and Voicu 2020).

Valuable products can be recovered from wastewater. The use and market value of these products are subject to public participation and social acceptance. Cellulose fibers are recovered from urban waste water in the Netherlands. Most of the suspended solids in the wastewater in the country are toilet papers flushed into toilets (Kehrein et al. 2020). It is unclear whether the process that offers a sustainable approach and will produce raw materials for toilet paper from cellulose fibers will be accepted by the public.

In developing societies, old consumption habits and certain behaviors brought about by cultural values pose an obstacle for a sustainable new world. Fundamental environmental culture can be instilled in people of all ages, yet this will take time. Developed countries are more eager to transform waste into valuable products (Akhtar et al. 2015). This is due to their sufficient knowledge, high level of welfare, sufficient technical knowledge, and advanced infrastructure systems. On the other hand, since developing countries are deprived of most of them, they aim to create waste management by providing maximum employment with the lowest investment cost.

The deposit-refund system is profitable for recyclable packaging and metal waste besides its environmental benefits. Contamination of these valuable wastes with other organic pollutants brings some pre-treatment applications. In order to avoid this costly process, strategies should be developed to expand public awareness and encourage a clean waste strategy.

Overall, municipalities' waste management strategies are limited in the existing form. Public support and attitude towards practices where waste is transformed into products is indispensable.

7. Regulatory Challenges

For the implementation of resource recovery projects, stakeholders, the state and the municipality should work together in a consistent manner. Governments need to set quality standards to ensure the use of recovered product. Cities are having trouble increasing the incentives of countries to reuse water in national and local water management planning. The high initial investment costs of recovery technologies prevent cities from adapting and taking action on this. Where the state's financial resources are insufficient, arrangements are needed to engage private sector support.

Zero Waste Europe program intends to adopt the holistic approach of zero waste by countries with many projects and policies. In the Zero Waste Europe program, it is aimed to adopt the holistic approach of zero waste by countries with many projects and policies. A comprehensive program that covers many topics such as waste strategies, zero waste cities program, consumption and production systems, climate energy and air pollution, plastic pollution, chemical recycling and waste trading (EU, 2019).

The Green Deal, Circular Economy Action Plan and Sustainable Product Policy Framework increase the incentives for more sustainable and circular products by adopting a zero-waste policy (EU, 2019).

It has been challenging to make action plans and come up with concrete solutions on the circular economy in the waste and water sectors. Recyclable building design and a new circular economy model are developed in order to increase the circularity in the building sector. In addition to new business opportunities, projects that encourage the use of construction and organic wastes as raw materials attract attention. At the same time, the "Plasticircle" project allows the plastic looping. It is being implemented in Romania, Spain and the Netherlands in the pilot city phase. For bio- waste, food wastes and wastewater sludge fourteen different projects were developed. The common goal of these projects is to gain valuable products with bio-refinery technologies (HORIZON2020).

Resource Recovery Framework sets rules to promote resource recovery as well as eliminate restrictive situations for product use afterwards. The framework pioneering the safe and beneficial use of waste and supports the transformation of waste into fertilizer, water and energy (EPA, 2021). The applying compost and bio solids to land fact sheet serves as a guide for the application and useful use of compost and bio solids to the soil, it gives information about the rules under which organic wastes will be applied (EPA, 2021).

In Queensland the government has created a comprehensive 10-year roadmap and action plan for resource recovery and zero waste generation instead of sending waste to landfills. Australia targets to become one of the leading countries in recovery strategies. Also, it aims for an investment of 100 million dollars due to the creation of new job opportunities and environmental benefits (State Development, 2019).

Table 2. Regulations, legislations and frameworks for sustainable circular cities

Country/ Continent	**Regulations, Legislations**	**General information about regulations, legislations, actions and plans**
	Actions and Plans	
Europe	Zero Waste Europe	Based on holistic approach for waste strategies
	Green Deal	
	Horizon 2020	Comply with zero waste cities program
	Circular Economy	Focus on consumption &production systems, climate energy, air pollution
	Action Plan	
	Sustainable Product Policy	Related with plastic pollution, chemical recycling and waste trading
USA	Resource Recovery Framework	Pioneering the safe and beneficial use of waste and supports
		Includes transformation of waste into fertilizer, water and energy
Australia	10 year road map	Related with resource recovery and zero waste generation
	Resource Recovery	Aim is not sending waste to landfill
	Action	
Turkey	Waste Management Regulation	Industrial symbiosis applications, deposit application
		Includes license obligation for industries,
		circularity in raw material supply,
	Zero Waste Project	evaluation and minimization of waste

The primary practices that ensure circularity in raw material supply and production stages are the recovery and industrial symbiosis applications inside or outside the facility, also the evaluation and minimization of waste. Waste Management Regulation in Turkey serves this purpose. Companies can be exempted from the license obligation if they recover their wastes in their own production sites. However, they must notify the Ministry and obtain conformity approval. Firms can also sell their recovered materials in accordance with the approval of the Ministry. On the other hand, under the leadership of the Ministry of Environment and Urbanization, the end-of-waste (EoW) criteria were determined within the scope of the EU harmonization studies, and the project studies were carried out with the support of the EBRD, the road map for this was determined and the studies were planned to continue with a new EU-funded project. Zero Waste Project was initiated by the Ministry of Environment and Urbanization in 2017. With this project, it is emphasized that waste is also a resource and waste management should be handled in this way. The deposit application, which is currently under preparation, is expected to start in 2021 (Circular Economy Platform, 2020).

Finally, resource recovery projects require strong ambition and high political support; otherwise tackling difficulties can complicate the process. On the other hand, defining goals correctly, setting a scope to make things easy and evaluation means carefully organizing the coordination of all elements.

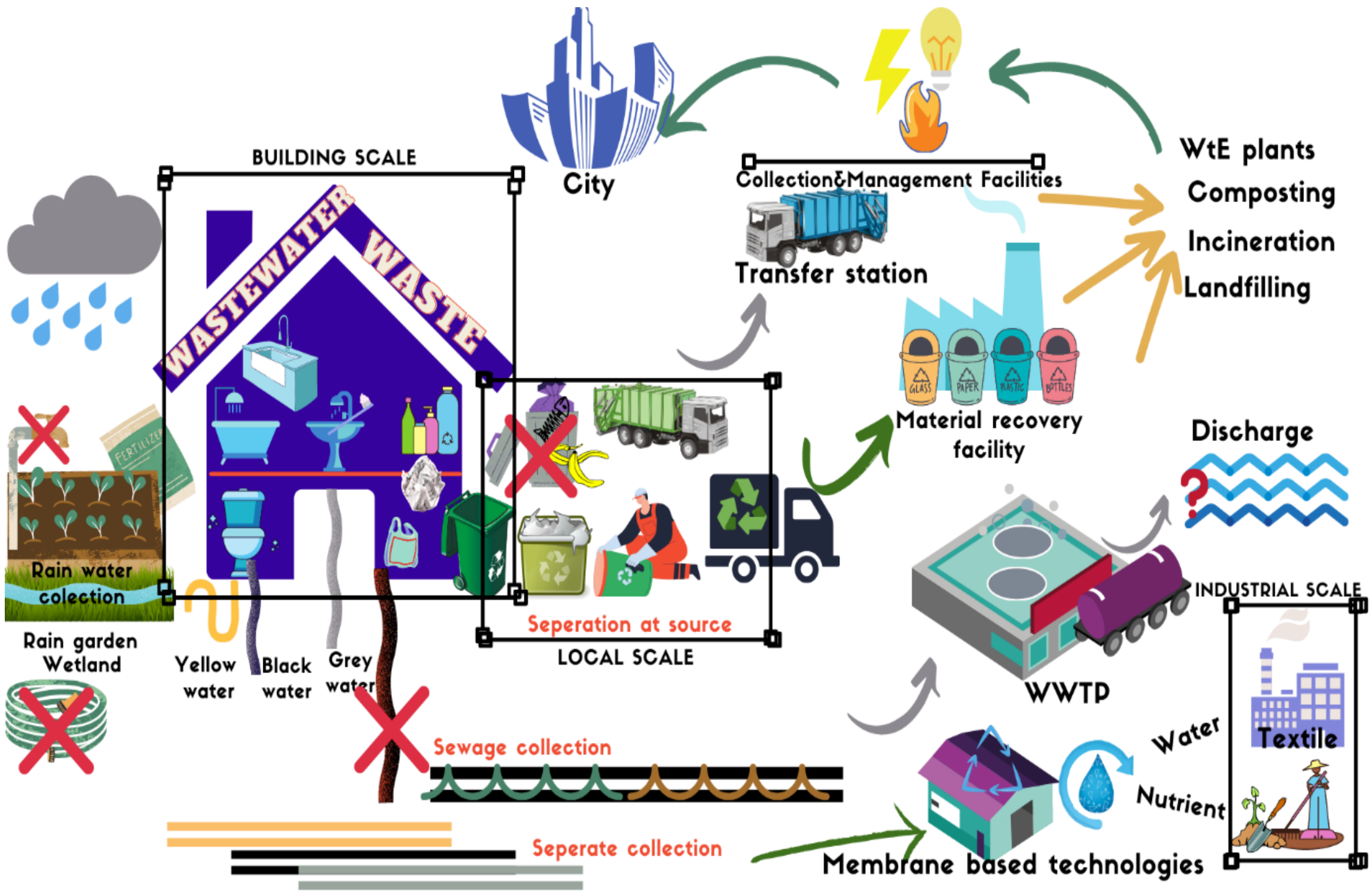

Figure 3. Overall waste management strategies in building, local and industrial scale in a city.

CONCLUSION

Linear cities are progressively evolving into circular cities with the encouragement of new guidelines and promotions provided by Environmental Agencies of the regions. Transformation process needs time and brings some challenges. First of all, technical challenges can be varied in terms of infrastructural aspects such as water and wastewater collection system and waste/wastewater management and waste to energy plants. Infrastructural challenges are concerning the building systems and local authorities. Not only the infrastructure of municipalities for waste/wastewater collection, but also design of buildings can significantly be affected by transformation of linear cities to circular ones. Municipality has high responsibilities in local scale; they need to support building contractors for the new infrastructure and to rebuilt waste/water collection systems and their management facilities. In addition to municipalities, industries will be affected in terms of infrastructural needs since they will have to adopt their existing waste/wastewater management to the circularity. Technological challenges for waste/wastewater management facilities include old and improper infrastructure, scale-up, pretreatment needs, poor performance, improper design, optimization, time intensity, sensibility, operation quality, uncertainty about longevity and performance, lack of data. Second group of challenges is the undesired environmental damages as a result of waste management activities and environmental damages of the products generated. Thirdly, economic constrains are revealed. While determining the new model for cities, it is necessary to allocate a very high budget for adaptations and new investments. At the same time, operational and maintenance costs can limit the budget according to the development needs. The market value of the resulting product must be high. This can be supported by financially profitable incentives and promotions. It is important to make a budget planning with all items considered, from training the labor force to the change of the infrastructure system. Another challenge for circular cities, some human oriented situations may occur. With mechanization and new technologies, the need for manpower may be decreased. This situation causes the disappearance of some business areas. On the other hand, qualified people are needed in the design, installation and operation of new recovery systems. It requires a corporation with many disciplines. In addition to human resources, public acceptance is momentous in the waste management process. The recovered water, fertilizer and biomaterials should meet the needs of the people. It should be ensured that the public can use it safely and products should be supported with incentives considering the health of the public. In which part of the city the new or modified facilities operate creates a big problem in small cities. Lastly, regulatory and legislative challenges restrict technological innovations about reuse/recycle/recovery actions.

This study revealed that there are a number of technical, economic, environmental, human-resources, social and regulatory challenges in the management and recovery of various waste segments in cities. Overall, although it requires time, money and effort, these difficulties can be overcome with the laws and actions taken, sustainable closed loop system can be created where waste/wastewater turns into a product.

Further studies are highly recommended in the both scientific and management level in order to contribute to the solution of challenges which are mentioned in this chapter. It is clear that there are various technical, economic and environmental issues that needs to be clarified through scientific research. Best available infrastructure system to be implemented in the building and municipality scale and best practicable waste/wastewater recovery technologies that is proper to operate without complicated pretreatment and to scale up for high capacity applications are urgently needed. In addition to technical details, scientific research studies should focus on the economical feasibilities and reducing the environmental impacts of these technologies. Results of these scientific studies can also be complementary for solutions of the social and regulatory challenges. Regulatory makers and governmental authorities such as Ministries and Municipalities should be the main actors of the implementation process of circular cities. Cooperation of the authorities with the scientific stakeholders for the best practicable application and with the society for the public acceptance in the local scale can make the transition period to circular cities more efficient and smooth.

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Chapter 14

SUSTAINABLE MANAGEMENT OF AGRICULTURAL WASTE: PRESENT, PAST AND FUTURE

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ABSTRACT

Industrial and human activities are the main causes of wastes in nature which are continuously increasing day by day and adversely influencing the health of ecosystem as well as human community. Agricultural waste is one of the major environmental problems which can be generated through cultivation, livestock and aquaculture. Besides this, agricultural wastes also possess hazardous toxic materials which negatively affect the plants as well as human health. Such waste if properly managed then can be regarded as an important bioresource for enhancing food security. These organic wastes also contain high level of nitrogen, potassium, phosphorus and organic matter which are important for improving soil fertility and nutrient levels in the agriculture soil. Increased nutrient supply leads to improved crop yield as it also enhances the quality of soils. The efforts towards the conversion of agricultural wastes to value added products could be a sustainable approach towards waste minimization. This review is an attempt to explore the possible conversion technologies for agricultural wastes.

Keywords: agricultural waste, organic waste, value added product, sustainable development, waste management

1. INTRODUCTION

Improper waste management is a global problem and is detrimental to human health. Apart from being unsightly, it causes air pollution, soil contamination, affects water bodies

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when dumped into the water, and also affects the ozone layer when burnt, thereby increasing the impact of climate change (Ayilara et al., 2020). Agricultural waste is one of the major problems which are caused either by human, animal activities or by industries. It constitutes wastes from food processing, crops (straw of wheat and rice, residue of corn, sugarcane, fruits and vegetables), animals (manure, animal carcasses) besides hazardous and toxic agricultural chemicals (pesticides, insecticides and herbicides) (Obi et al., 2016). Increased growth in human population and expansion in agricultural production has resulted in increased amount of agro-industrial waste, livestock waste and agricultural crop residues. These wastes can be in the form of solid, liquid or slurries depending on the nature of agriculture activities. Agricultural waste has been found to be rich in by-products like sugar, fiber, mineral moisture and protein and phenol which can be biodegradable or non-biodegradable. The degradation of agro-waste occurs either by aerobic or anaerobic process. Compost is the result of aerobic transformation (Lasaridi et al., 2018), while biogas and biofertilizers are the example of anaerobic transformations (Khan et al., 2018). In composting process, complex materials are degraded and transformed by microorganisms into organic and inorganic by-products (Toledo et al., 2018). Since, agro-waste is found in large amount and easily available, there an urgent need to convert it into value added products for sustainable development. This chapter focuses on the waste minimization technologies and sustainable uses of agricultural waste.

2. Agricultural Waste Generation

Extraction of raw material, manufacture of products, consumption and improper waste managements are the sources of agricultural wastes. Besides this, global trade and urbanisation are also contribute towards waste generation. The agro-waste generation is also dependent on the types of agricultural activities associated with farming, food chain, application of fertilizers, pesticides and herbicides. Each and every stage and phase of the agriculture food chain can create significant agricultural waste (Adejumo and Adebiyi, 2020). The classification of agricultural wastes includes the following:

1) Crop production solid waste
2) Animal production solid waste
3) Food and meat processing solid waste
4) Medical soil waste
5) Horticulture production waste
6) Industrial agricultural waste
7) Chemical waste

Besides these, farming activities, poor road network, lack of rural electrification, lack of storage facilities, food spoilage and kitchen generated agriculture waste can be regarded as the source of agricultural waste generation (Klich, 2007; Jeremy et al., 2010; Nierman et al., 2015; Yangyang et al., 2016).

3. UTILIZATION OF AGRICULTURAL WASTE

Agricultural waste utilization technologies either use the residues rapidly or store the residue for gaining the end product in such a manner that residue can’t be spoiled. Various applications of the agricultural waste are being discussed here.

3.1. Fertilizer Application

Animal manure can be used as a fertilizer which has a large impact on the energy requirement at the farm level. It is regarded as the source of nitrogen, phosphorus and potassium in the fertilizer and increases the fertility of soil by increasing organic carbon in the soil (Council for Agricultural Science and Technology, 1975). Mokwunye (2000) reported that poultry manure has high content of phosphorus which is useful for the growth and productivity of crops.

3.2. Removal of Metal from Waste Water and Soil

Metal is one of the major problems in water and soil due to industrialization. Unlike organic pollutants, metals such as copper, zinc, chromium, cadmium, mercury and lead do not degrade and cannot convert into the end products. Agricultural wastes have proven to be a low cost alternative for the treatment of effluents containing heavy metals through the adsorption process. Use of low cost agricultural waste such as coconut husk, sawdust, neem bark, rice husk sugarcane bagasse and oil palm shell for the elimination of metals from wastewater, has been investigated by various researchers (Tan et al., 1993; Ajmal et al., 1996; Ayub et al., 2001; Ayub et al., 2002; Mohan et al., 2002; Khan et al., 2003). Some authors also reported that aromatic plants can also be grown in the metal polluted soils (Zheljazkov et al., 2006; 2008 a, b; Stancheva et al., 2009; Affholder et al., 2013; Kunwar et al., 2015; Bisht et al., 2019).

3.3. Anaerobic Digestion

Anaerobic digestion is a technology by which all sources of biomass including organic waste, manure and slurry can be converted into a highly energetic biogas (Holm-Nielsen, 2009). Agricultural waste, particularly manure is a good option for generating methane gas which is used for heating purpose of boiler, water etc. So, it is an effective and ecofriendly process for recycling the agricultural by-products.

3.4. Direct Combustion

Combustion is an easy and old technology to convert all types of agricultural wastes into energy and fuel. The complete combustion of agrowaste material gives oxidative products of organic matter, carbon dioxide, water and some ammount of energy also released (Klass, 2004). This energy is utilized for the combustion of biomass. Thus, combustion can be used for waste utilization (Horvat and Dovic, 2018).

3.5. Pyrolysis

This tehnology is used for the conversion of agricuture waste into bio-char material. In this process, the agricultural waste is heated at very high temperature (400-600 ℃) in absence of oxygen (Amonette, 2009). Pyrolysis of agriculture waste produces biochar and low heating value gas oils. Besides this, some other techniques like hydrogasification and hydrolysis are also used for the preparation of chemicals from agricultural waste as well as energy recovery.

4. VALUE ADDED APPLICATIONS OF AGRICULTURAL WASTE

The agricultural waste can also be managed in such a way that it enhances the quality of air, water and other resources without adversely affecting the natural sources. Some of useful applications of agricultural waste are shown in Figure 1.

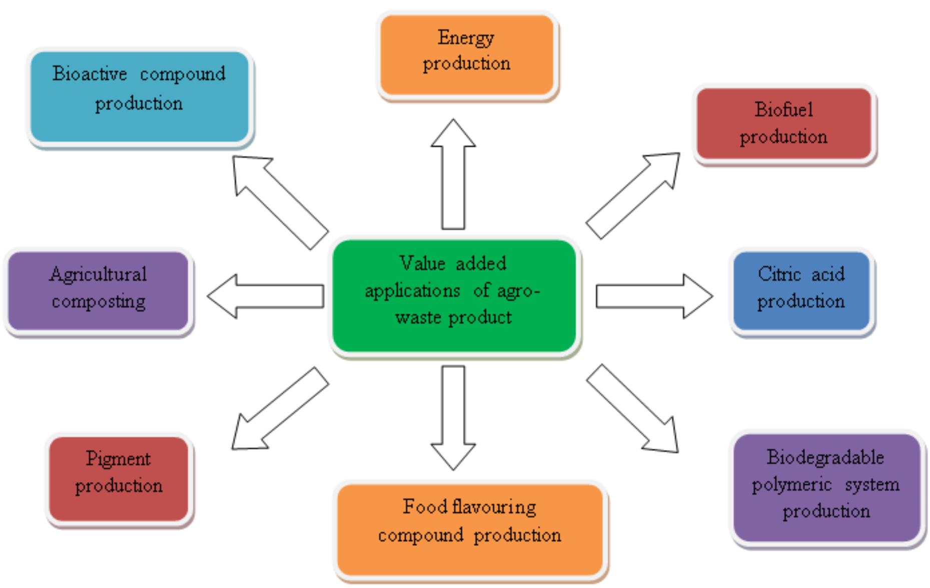

Figure 1. Value added application of agro-waste product.

4.1. Biofuel Production

World's economy is dependent on the fossil energy sources like coal, petroleum oil, natural gas etc. which are used for the production of fuel and other purposes. The excessive use of these fossil energy sources create pollution by emerging green house gases and also affect ozone layer. To prevent our environment from these negative impacts, we should effort to generate these sources by agrowaste material. The renewable sources might serve as an alternative option. For example, wind, water, sun, biomass, and geothermal heat can be the renewable sources for the energy industry, whereas fuel production and the chemical industry may depend on biomass as an alternative source in the near future (Sarkar et al., 2012).

Bioethanol production is a renewable alternative to replace fossil fuels from agro-industrial wastes. Kim et al., (2004) estimated that bioethanol can be produced from biomass (crop residue). The preparation of bioethanol from agricultural wastes can be achieved through various processes such as fermentation, pyrolysis, physical treatments, physico-chemical treatments, enzymatic degradation and ultrasound-assisted treatments. Proper pretreatment methods can increase concentrations of fermentable sugars after enzymatic saccharification, thereby improving the efficiency of the whole process. Conversion of glucose, as well as xylose, to ethanol needs some new fermentation technologies, to make the whole process cost-effective (Bharathirajaet al., 2017). Nevertheless, the production of bioethanol requires in-depth studies so that cost-effective, cheap, and best complementary technologies could be made.

4.2. Enzyme Production

Enzymatic hydrolysis is a very significant technique for the conversion of agricultural waste into valuable products. By using agricultural waste, we can reduce the production cost and increase the use of enzymes for industrial purposes. Agro-industrial wastes like wheat straw, sugarcane bagasse, rice bran, wheat bran and corncob are the cheapest and have plentifully available natural carbon sources which were utilized for the production of industrially important enzymes (Jecu, 2000).The utilization of agricultural wastes substrates and by-products have been successfully reported for the production of cellulases (Salim et al., 2017).

4.3. Pigment Production

Fermentation process is widely used for the development of value added products like microbial pigment. These pigments have advantage like biodegradability, zero or less toxicity, and eco-friendliness with their synthetic counterparts (Yusuf et al., 2012; 2015;2016; 2017). *Monascus purpureus* is found to have good ability to ferment the agroindustrial waste to produce yellow pigments. The pigment colour of microorganism (bacteria, fungi etc.) depends on their sources. Some well-studied microbial strains that have potential of bio-pigment production from wastes are belonging to genera *Monascus, Rhodotorula, Aspergillus*, and *Penicillium* (Dufosse, 2006; Mendez et al., 2011; Panesar et al., 2015).

4.4. Citric Acid Production

The organic wastes genterated from agriculture and industries have been found to be rich in sugar and carbohydrate contents. The presence of moisture, nutrients, and large carbon sources can be fruitfully utilized for the production of a variety of value added compounds/products. Keeping in mind the demand of citric acid, there is an urgent need to develop the technologies for the production of citric acid by using wastes. Fermentation is the most common technique for the production of organic acids, by which the production of citric acid is economical but the main advantage of this method is easy to handle, stablility, lower energy consumption and convenient. Tran et al., (1995) reported that pineapple wastes are better options for biomass-assisted citric acid production than apple pomace. The citrus processing industries generate a large amount of waste which can be utilized for the production of citric acid (Torrado et al., 2011). The organic acid prepared using agro-industrial wastes by solid-state fermentation processe through several microbial isolates are shown in Table 1 (Couto et al., 2006; Loh et al., 1996; Soccol et al., 2006).

Table 1. Organic acid prepared using agro-industrial wastes

S. No	Agro-industrial waste	Microbial isolates	Product obtained
1	Kitchen wastes	Self-inoculated, Media/ isolates	Lactic acid, acetic acid, propionic acid and butyric acid
2	Tea wastes with sugarcane molasses	*Aspergillus niger*	Gluconic acid
3	Wheat kernels	*Aspergillus oryzae*	Oxalic acid
4	Carrot-processing waste	*Rhizopus oryzae*	Lactic acid
5	Sugarcane bagasse	*Rhizopus oryzae*	Lactic acid
6	Pineapple wastes	*Aspergillus foetidus*	Citric acid
7	Apple pomace, potato starch residues, coffee husk, orange peel, corncob, sugarcane bagasse, wheat bran, rice bran, pineapple waste, mixed fruit waste, beet molasses, date syrup, wood hemicellulose, rice hulls, cassava fibrous residue, palm and olive oil residues, etc.	*Arthrobacter paraffinens, Bacillus licheniformis Corynebacterium sp. Aspergillus niger A. aculeatus A. carbonarius A. awamori A. foetidus A. fonsecaeus A. phoenicis Penicillium janthinellum Candida tropicalis C. oleophila C. guilliermondii C. citroformans Hansenula anomala Yarrowia lipolytica*	Citric acid

4.5. Extraction of Bioactive Compounds

The wastes obtained from fruits and vegetables are rich sources of bioactive compouds particularly polyphenols which are good antioxidants. Further, it has been reported that carotenes, terpenes, sterols, tocopherols and polyphenols extracted from tomato waste exhibited good antimicrobial and antioxidant activities (Kumaret al., 2017). Similarly, Pujol et al., (2013) reported that the amount of polyphenols and tannins are quite good in coffee waste.

4.6. Extraction of Food Flavouring and Preservative Compounds

Agro-industrial wastes are sustainable and renewable resources for the production of value-added products. With the help of microbial conversion processes, we can produce natural flavouring agents from agricultural waste. Vanillin, a well known flavouring agent, can be obtained by the use of agrochemical waste by-products. Similarly, ascorbic acid, a natural compound obtained from plant tissues is an example of preservative compound used in food industry. Vitamin C is also used as a natural medicine and food preservative (Ayala-Zavala et al., 2009). Similarly, the citrus species wastes have been used to preserve cheese and other food products.

4.7. Recycled agricultural composting

Composting is a managed process which utilizes microbes for the detoxification of the soil and supression of environmental pollution (Garg, 2017). Microbial population degrades the complex substances present in the biomass to simpler ones that can be reused or recycled through environmental processes (Franchi et al., 2016). The degradation techniques depend on the type of microbes (fungi, bacteria etc.) which reduces the soil toxicity, promotes plant growth and provides plant nutrients (Gkorezis et al., 2016). Thus, the bioremediation of agricultural waste could be an effective toolfor agriculture benefits.

Conclusion and Future Perspective

The sustainable management of agricultural waste has become a great challenge due to globalization and industrialization. Agrowaste can be used by different techniques in such a manner that it can meet the demands of the present generation. Keeping this in mind, government organisations are continuously promoting innovative research to handle agriculture waste. The uses of agrowaste by different techniques and by products are discussed in this chapter. The conversion of agrowaste residues to important substances may not only provide future dimension but also contribute towards environment saftey.

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Chapter 15

WASTE MANAGEMENT USING TPM PILLARS IMPLEMENTATION – A CASE STUDY

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ABSTRACT

Total Productive Maintenance is an innovative approach to maintenance that increases equipment effectiveness and its utilization by eliminating breakdowns, increasing equipment performance and by promoting autonomous maintenance by the operators. The present study has been carried in a forging industry to improve the OEE of its particular section. A bottleneck machine was identified and four TPM pillars viz. 5S, Autonomous Maintenance, Planned Maintenance, and Quality maintenance were implemented. Overall equipment effectiveness was evaluated before and after TPM implementation pillars on the Bottleneck machine. Results of investigation demonstrated net improvement of 15% in availability, 4% in performance efficiency, 0.3% in quality rates which results in improvement of 13.77% in overall equipment effectiveness. Case Company was also benefited in reduction in time losses, breakdown of machine and increased machine utilization.

Keywords: total productive maintenance, overall equipment effectiveness and case study

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INTRODUCTION

There is always a need for treating maintenance as an integral part of production and also as a part of business strategy for achieving a world class status, which requires increasing demand on product quality, productivity and availability of equipment and machinery in improved operating conditions (Bamber et al. 1999). In order to survive and sustain their businesses under those new competitive conditions, companies are forced to enhance their operations' effectiveness; thus providing a competitive advantage that is difficult to imitate (Hayes and Upton 1998; Gill and Johnson 1991). The manufacturing industry has experienced an unprecedented degree of change in the last three decades, involving drastic changes in management approaches, product and process technologies, customer expectations, supplier attitudes as well as competitive behavior (Ahuja et al. 2006). The inadequacies of the maintenance practices in the past, have adversely affected the organizational competitiveness by reducing throughput and reliability of production facilities. This has resulted in fast deteriorations in production facilities, lowering equipment availability due to excessive system downtime, lowering production quality, increasing inventory, thereby leading to unreliable delivery performance. As organizations in today's highly challenging scenario have moved to reduce costs and improve quality and responsiveness, the reduction in inventory and excess capacity have revealed serious weaknesses in the traditional maintenance programs (Lawrence 1999). Thus, as a significant contributor towards organizational endeavors of growth and development, there is an utmost need to improve efficiency of maintenance function in the organization. The productive success in today's manufacturing climate depends upon the implementation of multiple complimentary and proven strategies. Total productive maintenance (TPM) is the proven manufacturing strategy that has been successfully employed globally for the last three decades, for achieving the organizational objectives of achieving core competence in the competitive environment (Ahuja et al. 2004; Bamber et al. 1999).

Competitive pressures and changing production management paradigms, in recent years, have increased the importance of reliable and consistent production equipment. The recent competitive trends have been pushing manufacturing organizations to reconsider the significance of increasing equipment availability and utilization, maintenance productivity and resource utilization, and of enhancing the quality and responsiveness of maintenance services to meet the organization's goals to achieve world-class status. Equipment management has received significant attention in recent years in the manufacturing industry because of the industry's dynamic characteristics and the increasing cost of capital equipment (Oke 2005; Singh and Ahuja 2015). The present study has been carried out in auto parts manufacturing company of northern India that was facing issues like, time losses due to setup change, low OEE, tooling failure, equipment breakdown; rework losses etc. due to which the machines were not utilized effectively and hence production rate and volume ware affected which further results in shortage of dispatch vs order ratio leading towards high premium freight. Systematic procedure or steps of implementing TPM pillars has been followed to ascertain the benefits occurred.

The remainder of the chapter is divided into four sections. Literature review section includes literature justifying role of OEE towards operational performance improvement, literature justifying six major losses as a part of OEE through TPM, Literature justifying the role of TPM and TPM pillars towards performance improvement; next section describes research framework and methodology adopted for research; further section describes the detailed implementation steps of TPM pillars implementation and benefits occurred; and finally conclusions, practical implications and limitation of the research are presented.

LITERATURE REVIEW

Literature Justifying OEE as Measure of Operational Performance

OEE methodology embodies metrics from all equipments in manufacturing states to measure and improve existing performance of equipment and, thereby, reducing cost of ownership (COO) of equipments (Ahuja and Khamba 2007). Bamber et al. (2003) have recognized and emphasized the effectiveness of OEE as an appropriate measure to evaluate and ensure the "healthy" operation of individual equipment or manufacturing process. OEE was proposed by Nakajima, which is basically a metric to identify potential areas for productivity improvement which would result in increased equipment effectiveness by evaluating three main factors of OEE, namely, availability, performance and quality (Nayak et al. 2013):

$$\text{Availability} = \frac{\text{Loading time} - \text{Down time}}{\text{Loading time}}$$

Performance efficiency (PE) = Operating speed rate * Net operating rate

$$\text{Operating speed rate} = \frac{\text{Theoretical cycle time}}{\text{Actual cycle time}}$$

$$\text{Net operating rate} = \frac{(\text{Processed amount})^{*}\ (\text{Actual cycle time})}{\text{Operating time}}$$

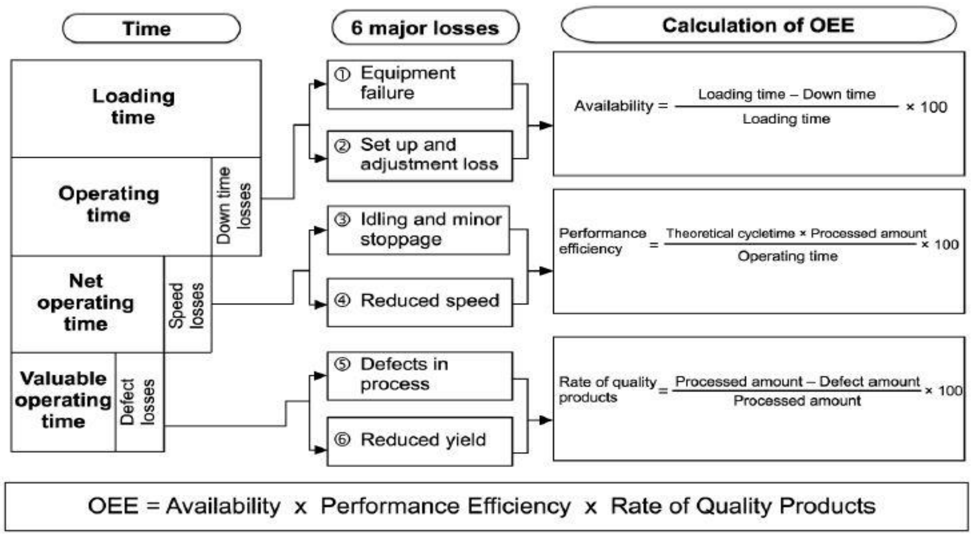
$$\text{Quality rate (Q)} = \frac{\text{Processed amount} - \text{Defect amount}}{\text{Processed Amount}}$$

OEE = (Availability)* (Performance Efficiency)*(Quality Rate) {Blanchard 1997; Al-Dahidi et al. 2016}.

Dal et al. (2000) reported that OEE not only helped to measure the improvement in the area in which it was implemented but also that it enabled new levels of performance measurement to be introduced. OEE provides useful benefits as a production monitor; it is as a measure of improvement that the real potential of OEE can be seen. If this measure is used not just to monitor but to manage improvement, OEE will provide a useful guide to aspects of the production process where inefficiencies can be targeted (Ericsson 1997).

Literature Justifying Six Major Losses as a Part of OEE through TPM

TPM uses OEE as a quantitative measure for gauging the production systems' performance by minimizing losses. The components of this strategy include cross-functional teams to remove machine uptime barriers, rigorous programs of preventive maintenance, improved maintenance operations management efficiency, training for equipment maintenance to the lowest level and information systems for supporting the development of imported equipments with higher reliability and lower cost by minimizing six major losses (Ahuja and Khamba 2008).



Source: Parikh and Mahamuni 2015.

Figure 1. Calculation of Overall equipment effectiveness (OEE) based on six major production losses.

The various disturbances usually occur in manufacturing processes during breakdown. They consume resources without adding any value to the final product. OEE attempts to identify these losses. OEE can therefore be defined as:

> "A bottom-up approach where an integrated workforce strives to achieve overall equipment effectiveness by eliminating the six big losses" (Nakajima 1988).

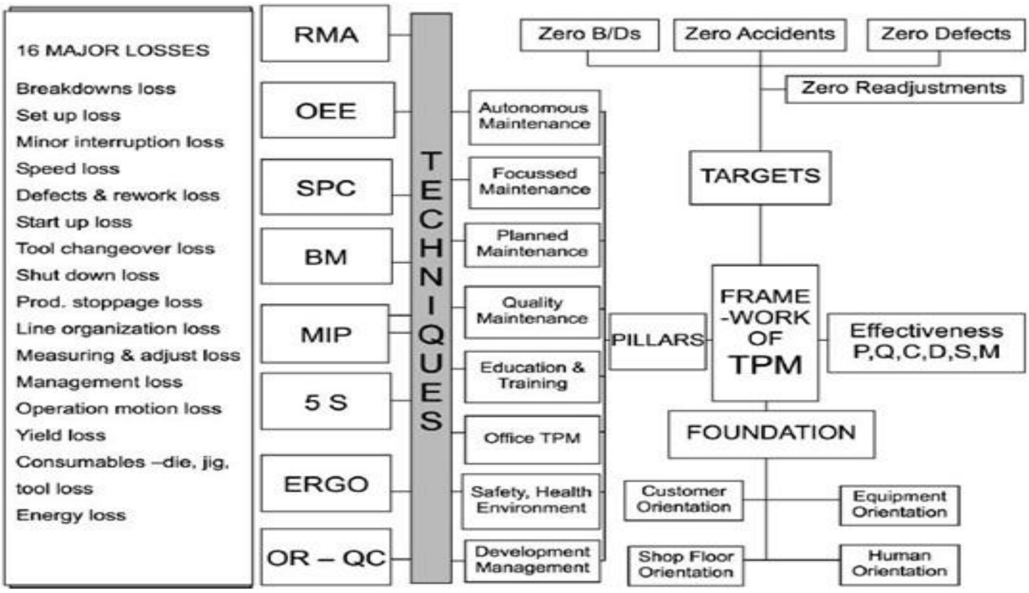
The first two big losses are known as downtime losses and are used to help calculate a true value for the availability of a machine. The third and fourth big losses are speed losses that determine the performance efficiency of a machine, i.e., the losses which occur as a consequence operating at less than the optimum conditions. The final two losses are considered to be losses due to defects, the larger the number of defects the lower the quality rate of parts within the factory so it is part of OEE (Dal et al. 2000).

Literature Justifying the Role of TPM towards Performance Improvement

Ahuja and Kumar (2009) carried out case study at a precision tube mill that has successfully implemented TPM and has reaped significant benefits as a result of TPM implementation. The study reveals that strategic TPM initiatives can significantly contribute towards the improvement of manufacturing performance in the organisation, leading to the realisation of core competencies for meeting global challenges. Martomo and Laksono (2018) presented the TPM implementation case study at PT Apac Inti Corpora in the spinning section on the ring frame machine. Due to high downtime because of breakdown and reduced speed of the machines, company was facing loss of production. OEE value calculated which was 79.96% on the ring machines. Then identification of losses were done to improve the process. Finally recommendations were given to work on operators training and to enhance their skills for autonomous maintenance and root cause analysis were done to find the cause of breakdown and performance reduction of machines. Sharma et al. (2017) analyzed OEE after selecting the model machine. The study was conducted in the piston manufacturing line in production. OEE is calculated before Implementation of TPM and found 60%. OEE is increased by reducing TPM losses such as i.e., downtime losses, set up loss and adjustment losses and improving operator's performance. By implanting TPM productivity was increased and there is improvement in OEE and after TPM OEE was 65%. Kumar and Rawat (2014) presented that losses were reduced and cost cutting was done in M/s Shiv plastics pvt. Ltd company by introducing and accepting TPM concepts in the organization. There was huge enhancement in the productivity levels. Systematic improvements were done with the use of TPM. The overall equipment effectiveness was increased from 79.38% to 85.44%in the company before and after TPM implementation. There was increase in availability and performance. Nzewi et al. (2016) explained that TPM requires the participation and engagement from the entire workforce to improve equipment availability, efficiency, performance, quality and reliability, TPM has to capitalize on operators, vendors, engineering, support group and management staff's knowledge and cooperation to cultivate a proactive and progressive culture in equipment maintenance methodology. To sustain this, employees must be empowered with the knowledge and skills through training, and the resources needed. In major improvement project, they may be required to share their success story with top management. Succinctly, top management commitment and leadership on its own is not sufficient for TPM success.

Literature Justifying Role TPM Pillars towards Performance Improvement

The components of TPM include cross-functional teams to remove machine uptime barriers, rigorous programs of preventive maintenance, improved maintenance operations management efficiency, training for equipment maintenance to the lowest level and information systems for supporting the development of imported equipments with higher reliability and lower cost (Tripathi 2005). Figure 2 shows implementation of TPM pillars leading towards performance improvement.



Source: Waghmare 2014.

Figure 2. TPM pillars implementation process.

Maintenance has become more challenging in the current dynamic business environment. It is considered one of the important strategic decisions in operations management as result organizations are deploying TPM pillars (Russell and Taylor 2009). *Singh and Singh (2014)* identify improvement related critical areas for ascertaining and to improve the manufacturing performance of an auto part manufacturing plant TPM pillar viz.. autonomous maintenance. This paper highlights the contributions of maintenance function to ensure enhanced equipment improvement related issues, thereby affecting improvements in the manufacturing system performance. Results indicated the average improvement in overall equipment effectiveness (OEE) of about 4.15%, reduction of 88.22% in rejections, decrease in down time of 7.125 hours/week and the net cost savings of $2,420. *Badli Shah (2012)* has concluded that the successful implementation of a TPM pillars can improve manufacturing performance, leading the organization to achieve a competitive edge and bringing a wide range of benefits. Maintenance cost can be optimized by using simulation-based models *Wakjira and Singh (2012)*, have said that TPM pillars in any organization enhances the OEE by increasing equipment availability and decreasing the amount of rework and rejections. The overall productivity of an industry can also be increased by TPM pillars implementation. TPM implementation makes favorable changes in the attitude of the operators, encourages a clean and attractive workplace and also increases employees' confidence and job satisfaction levels. From the eight pillars, the first four pillars are TPM elements that target to maximise production effectiveness and efficiencies, which have direct impact on manufacturing performance, while the other five pillars are supportive TPM elements that further enhance manufacturing performances (Nakamura 2008).

RESEARCH FRAMEWORK AND METHODOLOGY

The frame work of implementation of TPM pillars involves the following steps:

- Step 1: At the first step TPM pillars implementation team selection was selected. Team members were selected from different departments including systems, production, operations maintenance and tool room, so that there must be involvement of all the departments in implementing TPM pillars. It will ensure smooth workflow activities for the TPM work.
- Step 2: The next step involves the identification of bottleneck machine, brainstorming was done by the TPM team to select different critical factors on the basis of which bottleneck machine was selected. These factors are selected by team members by their past experience Critical factors that were selected are listed below:
  - Impact of machine on Production Volume
  - Availability of spare machine
  - No of Breakdowns in past
  - Downtime % in past
  - Die setup time
  - Defects produced
  - Defects resulted in customer complaint
  - Cost of spare parts
  - Bottleneck in the department
  - Unsafe condition around the machine
  - Dirt, dust and leakages
- Step 3: In this step ranking of 10 forging hammers utilized by the company is done based on the five point scale assigned based on production, quality, cost, delivery and safety. On the basis of considering all the factors, points were allocated to the ten hammer machines. These points were given as maximum 5 points for high impact of the factor and minimum 1 point for very less impact of the factor. At last sum total of all points for every machine was calculated and machine ranking was done and machine with maximum points was selected as the bottleneck machine. So, Hammer No 10 is selected as the bottleneck machine upon which TPM pillars were implemented. This machine is 1.5 ton hammer with high capacity than the others as other hammer machines are of 1 ton capacity. Also this hammer machine can produce some heavy components which can not be manufactured by small hammer machines. Some other features of this machine are that it is having high cost of spare parts. As spare parts of machine was also considered as important factor in selecting the machine.

For implementation of TPM pillars on the bottleneck machine methodology used has been used in Figure 3.

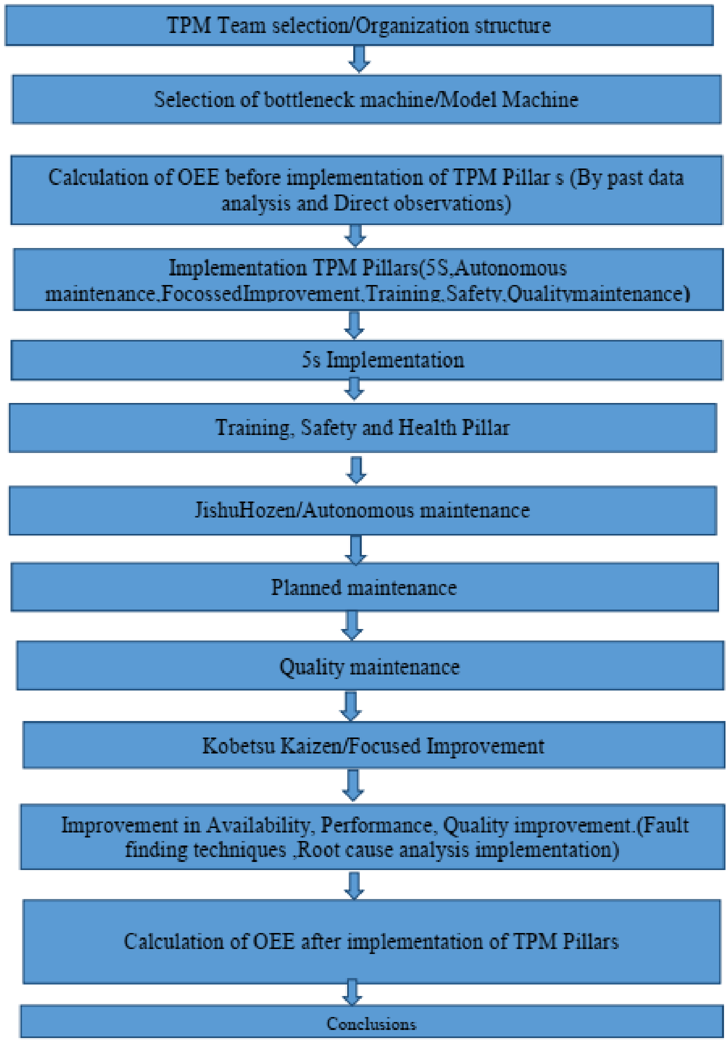


Figure 3. Methodology Adopted.

IMPLEMENTATION PROCEDURE OF TPM PILLARS

This section describes detailed steps of implementing four TPM pillars including 5S, Autonomous Maintenance, Planned Maintenance, and Quality maintenance; and Impact of implementing these pillars of OEE.

5S Implementation

It is a step by step process of housekeeping to maintain a clean environment in the work shop engaging the employees with a commitment to actively implement and exercise housekeeping. Difficulties cannot be visibly seen when the work shop place is dirty, unorganized. Problems can be seen clearly by Cleaning and organizing the workplace. Then making the problems visible is the basic first step of improvement (Randhawa and Ahuja, 2018). Figure 4 shows the procedure of waste elimination using 5S approach.

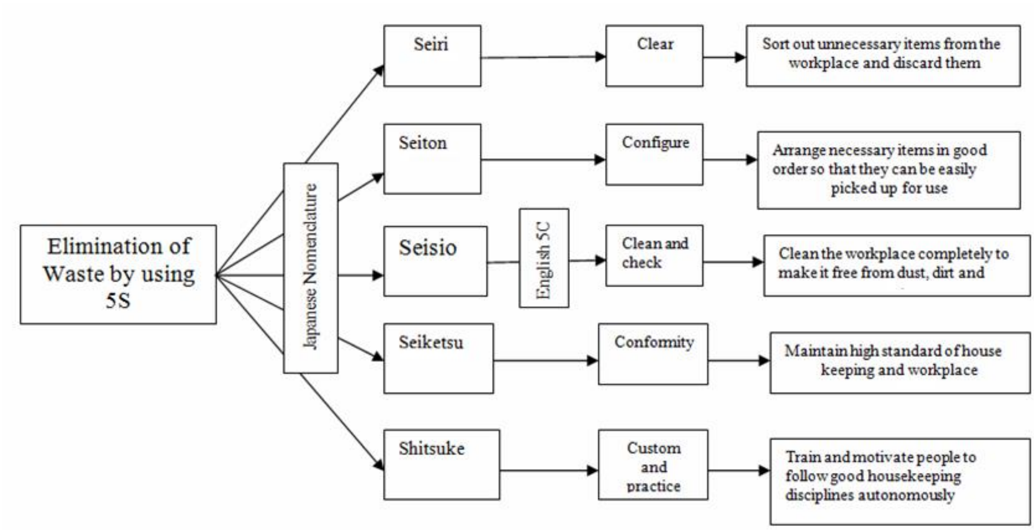


Figure 4. Waste elimination using 5S.

5S are defined as Sort, Set in Order, Shine, Standardize and Sustain. Because each of the five pillars begins with S, this process is appropriately named 5S. These 5S are implemented on TPM model section.

1) 5S – Sort: The first pillar of 5S helps to clearly distinguish the items that are needed in a work place from those which are no longer needed. At forging hammer no 10, various items have been sorted out on the basis of priority of use. The sorting out procedure has been shown in Figure 5.

Figure 5. Sorting in Hammer Shop.

2) 5S - Set In Order: In the second pillar, a place defined for every item so that it can be easily taken during need. The correct place, position for every tool, items required

and material must be chosen carefully in relation to how the work has to be performed and who will use them at what time.

3) 5S – Shine: The third pillar of 5S is needed to clean work areas, all work surfaces and equipment clean and free from dirt, debris, oil, etc. At hammer section all the persons from managers to operators were engaged for cleaning. In this step training is the provided to educate the TPM team about the safety equipments needed during the cleaning time. The safety equipments are shown in Figure 6-7-8.

Figure 6. Safety helmet.

Figure 7. Safety goggles.

Figure 8. Safety gloves.

4) 5S – Standardize: The fourth pillar of 5S defines the activities that are to be done at constant basis so standards are defined. Procedures, schedules and the persons responsible for keeping the workplace in a clean and organized manner.
5) 5S – Sustain: SUSTAIN is the last pillar of 5S and which makes the organization to be become disciplined in maintaining these new standards and procedures and in continuously improving the 5S state of the workplace.

Figure 9. Cleaning at trimming press.

Autonomous Maintenance or Jishu Hozen

With the fast change in the equipment improvement & automation needs, the scope of production had been separated into the operation and maintenance departments, which was expected only to produce & the maintenance was only estimated to do repairs but this thought had badly effected the apparatus Efficiency. Many breakdowns in machines may be prevented if some oiling, cleaning and tightening is performed by operators. The concept of Jishu Hozen was developed to change this mind set. This is often the fundamental condition of TPM. "Autonomous upkeep is the strategy by which machine administrators take and share duty (with upkeep division) for the proficiency and great condition of their possess equipment" (Robinson and Ginder 1995). This considering of the administrator that 'I fair work it' is to be changed by independent support. By TPM handle administrators are naturally spurred to keep the gear himself in great condition. The part of administrator isn't as it were to perform its operation but too to abdicate most elevated productivity of the machine by being effectively included within the support.

Table 1. Comparison of thinking of Production and Maintenance Departments

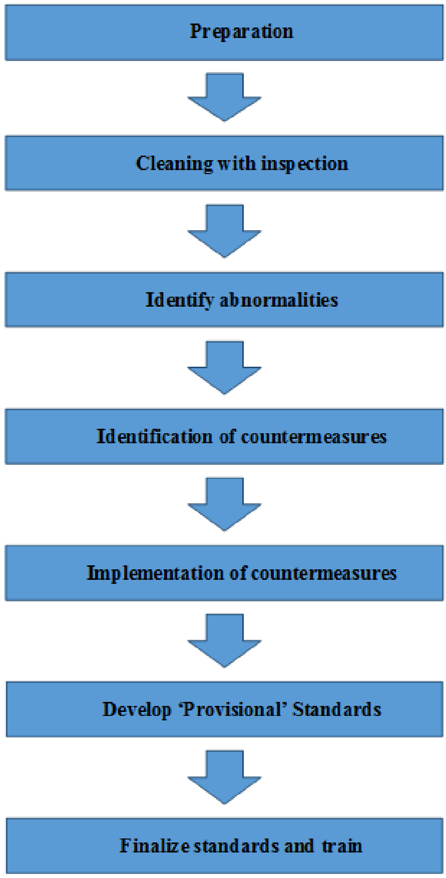
Production	**Maintenance**
1. Maintenance people do not repair properly.	1. Production do not know how to operate.
2. Maintenance people take too long to fix the problem.	2. We do not have time to do analysis because of lot of repair work.
3. We are too busy.	3. Machine is too old, there will be breakdown.

So what is needed:

- Without support of production people, it is not possible to do Maintenance of large no of machines by maintenance team. So involvement of production people is needed.

- As Operators are persons who spend most of their time near the machine & they know the machine very well so their participation for maintaining the machine is very important.
- There must be emotional attachment with the machine.

Steps to Autonomous Maintenance are shown Figure 10.



Source: Alsyouf, 2006.

Figure 10. Flow chart for Jishu hozen.

1) Preparation**:-** In the preparation phase general awareness is given to team members about the paybacks and importance of cleaning task, which comprises of knowledge about following questions:-
   – What is cleaning with meaning:

It concludes removal of all dust, oil, dirt, grease & other contaminants that stick to the surface of machine externally & internally. Cleaning means not just to clean but to take outrun of the seen problems in the apparatus condition.

Identify source of contamination.

Identify Hard to access area for below things.

- Cleaning
- Lubrication
- Inspection
- Tightening
- Adjustment
- Operating
  - Why we should clean the equipment:
    - Cleaning by using 5 senses becomes inspection
    - Then the Inspection converts into detection of abnormalities
    - Then Countermeasures for abnormalities are found which lead to restoration.
    - Restoration leads to equipment sustainability, maintainability & reliability (Positive effects)
    - Positive effects leads to motivation in workplace & thus change in the attitude of the operator.
  - Harmful effects of inadequate cleaning :
  - **-**Dirt and foreign matter penetrates rotating parts, sliding parts, electrical unit systems and sensors etc. & which causes breakdowns and failure.
  - **-**Quality Defects are caused either directly by the contamination of the component with dust, dirt or indirectly as a result of equipment fault.

2) Initial cleaning with inspection**:** This is the first step of the Jishu Hozen. Initial cleaning of the bottleneck machine (Model machine) and inspection is done. In this step of Jishu Hozen main focus is in finding abnormalities which lead to major breakdown or accident and remove them by taking corrective action against them.

Aim of Initial Cleaning

- Complete cleaning of machine with focus on improvement.
- Examine & uncover all of the abnormalities.
- Correction of the abnormalities.
- Basic condition of equipment is to maintain. In initial cleaning main concern is given to find the maximum abnormalities on the machine. These abnormalities are to be found by the maintenance personnel and the operators working in cleaning process. As maximum abnormalities are found, next step is to find countermeasures for these abnormalities. Countermeasures should be such that no repetition of the abnormality should remain the process. After that sources of the contamination were to be found and similarly hard to access areas were to be found and after that countermeasures were found for source of contamination and Hard to access areas. At the last provisional standards were prepared and these standards were finalized to be followed in future autonomous tasks.

In this phase actual cleaning of the machine is done in which team members from top management to machine operators taken part. Figure 11 shows the initial cleaning activities and Figure 12 shows the effect of initial cleaning.

Figure 11. Initial cleaning work at Hammer No. 10.

Figure 12. Initial cleaning effects.

3) Identification of abnormalities :In this phase maximum abnormalities are identified on the machine by applying tags which if not detected further lead to deterioration of the machinelike breakdown, quality issue, reduction in speed, accidents etc.

In order to countermeasure these abnormalities these are divided into two categories:

- Abnormalities to be corrected by the operators: Abnormalities that can be corrected by operators are given white tags. These abnormalities are corrected by the operators by their own within 24 hours. White tags which are put on the location of the abnormality area on the machine is as under: On the tag, information about the date, name of person who found it, and problem descriptions is given.

- Abnormalities to be corrected by experts e.g., maintenance, tooling, external experts: Abnormalities that are difficult to be corrected by operators are to be corrected by the maintenance engineers in 48 hours. These types of abnormalities are given red tag at the location. Below Figure 13 shows red tag that is placed on the abnormality.

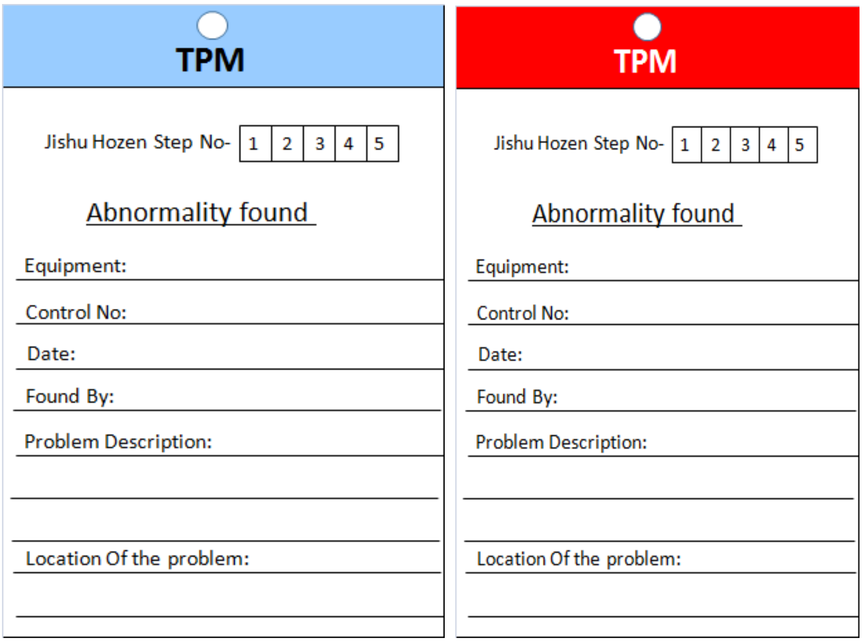


Figure 13. Red and white tags.

Guidelines for filling tags TPM tags:

1) Tags must be filled for each and every abnormality. For Example: If there are five bolts on one part of machine & all of them are loose then four tags should be filled.
2) Tags should be easy to understand and read i.e.,
   - Anyone should be able to read the writing.
   - The writer should use language which is comfortable to write for him.
   - Problem should be written very clearly.
3) Tags should be tied properly at the right location of the problem.
4) Take photographs of the tags & their location on machine & remove them before starting of machine so that tags will not disturb the operation or we can just leave the tags in the area which are not disturbing the process.
5) White tags should be removed in 24 hours and red in 48 hours

4) Identification of countermeasures for source of contamination and Hard to access areas:

What is contamination:

Contamination is a process by which anything gets dirty and polluted due to the presence of anything else which is not required at that place. So main motive is to find the root cause of the contamination and try to eliminate it.

Common contaminants that occur at the machine:

a) Dust
b) Dirt
c) Coolant
d) Oil
e) Powder
f) Rust
g) Paint peel off from the machine body
h) Metal particles

Effects of contamination

- Leaking of vapors and liquid leads to corrode the structures.
- Control becomes unreliable bye trace of dust, dirt, moisture in control panel makes.

KAIZEN SHEET

Before
Scales fall on the floor and contaminates the floor

After
Scales trapped by the suction blower at hammer.

Figure 14. Action against scales at floor.

Key points while taking action against source of contamination.

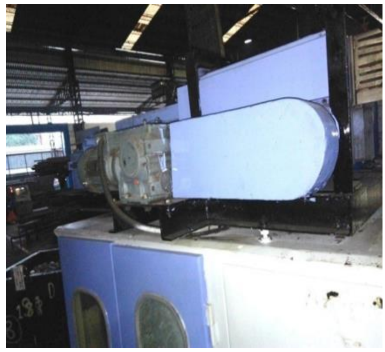
- Find root cause of source of contamination
- First try to reduce the area of contamination by localized guards and then try to eliminate the contamination if not possible

- First use guard made of card board without spending much money then after trial a permanent guard should be made.

1. Implementation of countermeasures: In this step, implementation of countermeasures identified in the previous step has been done. Different KAIZENs have been implemented on the critical machines to ascertain the important benefits occurred. Figure 14-20 shows examples of improvements that were done for increasing Overall equipment effectiveness.

KAIZEN SHEET

Before
No safety cover provided at conveyor chain



After
Safety cover provided at conveyor chain

Figure 15. Action against conveyor safety cover.

KAIZEN SHEET

Before
i. No tray is placed nearby induction coil furnace leads to scale deposition on floor .
ii. It leads to breakdown when scale comes in contact of air pipe

After
i. Tray is provided for scale collection.

ii. Chances of breakdown reduced

Figure 16. Action 1 against breakdown.

KAIZEN SHEET

Before

i. No position for hammer rope is defined

After

i. Adjustable rope block is placed on hammer for rope position

Figure 17. Action 2 against breakdown.

KAIZEN SHEET

Before

i. Floor contaminated with scaling during trimming process

After

i. Removable scale collecting box is placed on the trimming press to collect scale

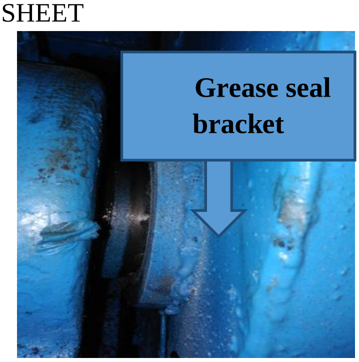
Figure 18. Action against floor contamination at trimming press.

KAIZEN SHEET

Before

Contamination with grease on grease cover during gear shaft rotation

No seal was available on the gear cover



After

Modified gear cover with grease seal bracket to stop grease leakage during rotation of the shaft.

Figure 19. Action against grease leakage.

KAIZEN SHEET

Before	After
No cover for gear motor and conveyor chain on ITF 10 causing possibility of accidents and also cause contamination of gear motor assembly.	Cover provided on gear motor and conveyor chain of ITF 10 for safety and reduction of contamination on gear motor assembly

Figure 20. Action against safety issue.

2. Development of provisional Standards:

It is very important to sustain the improvements done in last steps& that is done by making the tentative provisional standard. It has to be ensure that basic condition of machine is maintained & forced deterioration must be avoided.

Input should be taken from the past experience, break downs, quality defects, M/C manual & abnormalities observed.

- Operators have arranged and prepared standards for daily cleaning, lubricating, inspection &tightening as they have put lot of effort for cleaning their equipment, fixing the abnormalities & establishment of basic condition of machine.
- Operators have done many corrections against source of contamination & difficult to access areas. So Standards are self -made by the operators with the guidance of maintenance team.
- Standards are made using the 5W & 1 H technique.(what, where, when, why, who, how).
- Standards are easily understood by everyone as Self set standards are followed. As a result operator will become more aware of importance of maintaining their equipment in it’s newly purchased condition.
- Operator attached with equipment emotionally after completing all the above steps and they follow the daily inspection by their heart.

7) Finalization of the standards:

- Finally responsibilities are given to operators for their respective standards.
- Checking frequency for every point is defined for lubrication, cleaning etc.
- For every document, space is defined at the TPM board to be displayed as shown in Figure 21.
- Specific responsibility is given to the operators.

Figure 21. Displayed board for TPM documents.

Planned Maintenance

In this pillar the 5W & 1 H technique. (what, where, when, why, who, how) is used and time was defined for maintenance activity. This type of maintenance was generally done by the maintenance department according to the schedule for the machine, generally once in a month. With the implementation of TPM, engagement of top management was also increased so that any problem in maintenance activity can be escalated.

Quality Maintenance

This pillar is mainly concerned with the quality. The main aim of this pillar is to reduce the quality related problems and customer complaints and to improve the quality rate. Although, quality rate was already good as it was 98.3% in evaluated OEE before TPM implementation pillars on bottleneck machine. So little concern was given to the improvement of quality rate. In this pillar past data against rejections were taken and problem of side cut was identified as major rejection cause and why-why analysis was done taking machine into consideration.

Table 2. Actions taken for reducing side cut problem

Corrective Action(Why why analysis report)					
Problem	Why	Why	Why	Correction	Corrective Action
Side Cut	Due to component strike with trolley walls after trimming operation	After Trimming, pressman throw the pieces in the bin which strikes with bin angle	Because hot pieces after forging coming at constant intervals	Change in trolley design	Automatic conveyor provided below trimming die to transfer the trimmed material from press to trolley.

Kobetsu Kaizen/Focussed Improvement

Kobetsu Kaizen is a Japanese word which means focused improvement, in this importance is given to most significant losses and to eliminate them. These are distinct improvements and focus on the losses, when these losses are eliminated there is substantial improvements in terms of OEE (Chaneski, 2002).

To attain improvement in Overall Equipment Effectiveness, elimination of these "Six Big Losses" from the forging process are required.

- Break down losses: Due to breakdown in a machine or tool, these losses occur.
- Setup and adjustment losses: These losses of time that occur when there is setup and adjustment of dies.
- Idling and minor stoppage losses: Small losses that occur due to small frequent periods of machine, man idleness due to unnecessary reasons.
- Reduced speed losses: When any machine runs at the speed less than its design speed capacity, losses that occurs are reduced speed losses.
- Quality defects and rework: These are product related defects.
- Startup losses: These are the losses that occurs at the start of the production process during the start of the machine to the time at which it reaches its steady state.
- Kaizens to reduce setup and adjustment losses.
- Die setup is too much time-consuming processes. It starts with removal of the last die set up and to first part inspection. For conventional die setup there are 5 main steps:
- Preparation: This can be the primary step towards pass on changing in which we got to guarantee that all the dies are outlined appropriately.
- Mounting & Dismounting of dies: In this step, new dies are placed after removing firest die set.
- Establishing Control Settings: All sorts of settings like calibrations and estimations such as centering, measuring temperature are in this step of pass on setup.
- First Run Capability: In this step the fundamental alterations are done (re-calibrations, extra estimations) that are required after generation of to begin with trial pieces.
- Setup Improvement: In this last step of manufacturing pound pass on changing in which the time after preparing is included amid which the kicks the bucket are recognized, cleaned and tried for their usefulness some time recently their capacity.

In this kaizen, SMED concept is implemented in Forging Die change. Before implementing SMED die changeover time was 90 minutes and after implementing it becomes 12 minutes.

- 1st Stage: - In this Stage Separating of External and Internal setup is done.
- 2nd Stage: - Converting of Internal to External setup is done.
- 3rd Stage: - Streamlining of all the aspects of the set-up.

Below are some actions taken to reduce the die changeover time.

1. Bringing the die from tool room to Hammer: At first, the forging die was taken by operators from tool room during set up change. Now responsibility is provided to the tool room to bring the die to the hammer shop before setup change time. Now tool room department places the die on the rack by using loader machine. Before it was taken by operators as shown in Figure 22.

Figure 22. Improvement 1 during SMED.

2. Definite place was provided to place the die: Before implementation of SMED no place was defined to place the die .Operators place the die at any place on the floor, so there was more wear and tear of the die and improper space utilization was there, chances of accident was also there but after implementing SMED concept, a definite place was defined for the die.
3. Standard sized misters and packing used: Before implementing SMED mister keys and packing used were not of standard sizes which takes lot of time to adjust now standard mister and pacing is used. These are standard dimension of mister key758*48.2*35.5 (One end size).

Figure 23. Improvement during SMED.

Impact of Implementing TPM Pillars

Implementing SMED concept lead to tremendous time reduction dies changeover which directly affects machine availability as shown in Figure 24.

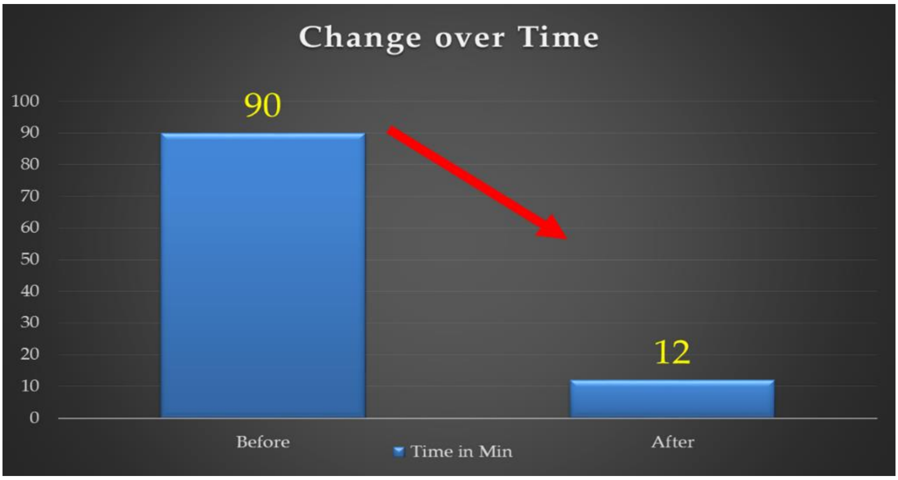


Figure 24. Reduction in changeover time.

Similarly, performance rate was 70% and it becomes 74% after TPM implementation. Generally, autonomous maintenance activities have done improvement in the performance rate of the machine, as number of small kaizens ware performed on the machine.

Quality rate was already good before TPM implementation which was 98.3 and it becomes 98.6 as not much focus was given on quality rate.

TPM implementation was started from January, 2019 to June 2019. Although, it is a long term process but improvement can be seen in the Overall Equipment Effectiveness trend. Below is the table 3 showing the month wise improvement in the OEE of the bottleneck machine.

Table 3. Increasing Trend in OEE from January 2019 to June 2019

S. No	Month	OEE
1	January	53.6%
2	Febroury	55.4%
3	March	58.8%
4	April	61.3%
5	May	65.7%
6	June	67.7%

Conclusion, Practical Implications and Limitations

It is concluded that TPM pillars focuses on optimizing. Availability, performance efficiency and quality yield (i.e., acceptable quality-rate) that affects overall equipment effectiveness. The present study outlines the significance of TPM pillars towards improving the effectiveness of machines and equipments associated with manufacturing system processes. Overall equipment effectiveness is a measure of six major losses arising in the manufacturing operations and can be enhanced by implementing standard procedure of implementing TPM pillars. The study includes identification of bottleneck machine by ranking criteria of critical factors that are identified by brainstorming and past experience of members of TPM team. There was significant improvement in availability from 78% to 93%, performance rate from 74% to 78%, quality rates from 98.3% to 98.6% which further results in improvement in overall equipment effectiveness from 53.6% to 67.37% for the bottleneck machine. In the TPM program, it is necessary to provide trainings and motivation at defined intervals of time to the operators and employees at higher level so that they should remain involved in the TPM process as TPM is a technique in which overall employee involvement is important to get desired benefits. The proposed implementation procedure not only will be useful to researchers, but also assists maintenance professionals of industrial organizations to find the significance that fit their specific needs. The limitation of the study is that OEE is not particularly prominent in the current performance measurement literature; within the near future its relationship with strategic business models will require further definition. Moreover, the selection of manufacturing industry has been done on convenient sampling technique.

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Chapter 16

BIOMEDICAL WASTE (BMW): HAZARDS, SAFE DISPOSAL, LEGAL ASPECTS, AND THEIR MANAGEMENT PERSPECTIVES

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ABSTRACT

The bio-medical services are required at every place and required to maintain 24X7 to cover the emergency needs. Therefore, lots of biomedical waste (BMW) is generated during diagnosis, treatment, or immunization of humans/animals. Also, it is generated from pharmaceutical companies, biomedical/biochemical/ biotechnology research activities to meet the progress. But, the component of BMW contains some pathogens/infectious and other hazardous things like the blade, syringe, etc. Thus, it is required to modulate the BMW management, their treatment, and proper disposal so that it may not risk the people vulnerable, other livings habitats, groundwater, soil, etc. Therefore, some rules and standards are defined by World Health Organization (WHO) to segregate, store, their treatment, and transportation. These rules mandate to be followed by the local hospitals, medical institutes, Municipal Corporation, BMW management and treatment facility owner, and other authorization. However, there are different methods of treatment of different types of BMW like autoclaving, microwaving, deep burial, and incineration. These methods must follow some standards/measures. But, these methods provide the disposal after treatment of different BMW under different conditions, and each has their advantages. But in the current era where we need to think to save our

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ecosystem and environment it is needed to bring the concept of 3Rs, namely, reduce, recycle, and reuse to the basic principle of BMW management and treatment. The best method for BMW management would be if we could produce some goods from it rather than disposing of.

Keywords: bio-medical wastes (BMW), types, BMW rule, management, treatment, deep burial, autoclave, microwave, incineration, risk

1. INTRODUCTION

Biomedical waste (BMW) Biomedical waste (BMW) is generated from the biomedical processes involved in health, veterinary, and other fields like biotechnology. It is mainly produced during the therapeutic diagnosis, medical or surgical treatment, and preventive steps during such activity, research, biomedical experimentation or immunization of human or animal research activities, and other aspects of biotechnology-related thereto. It is also produced during testing of the biological processes done in any health facility and camps. Its management follows an approach thatincludes its taxonomy, description, quantification, separation, storage, transport, handling and disposal (Gautam et al., 2010; Hirani et al., 2014).

3R's: **R**educe, **R**ecycle and **R**euse approach is followed in biomedical waste management and needed as the waste thus produced must be reduced during the generation process, after that recycling the waste and reuse if possible so that demand for new is also reduced. It certainly saves the resources and also the process cost of the article or object thus denoted as waste (Singh et al., 2014).

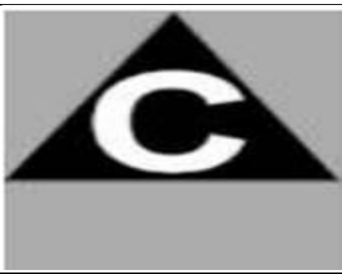
The BMW management is processed according to their desirability which includes mainly control on waste generation, recycle of waste after effective cleaning and sterilization, reuse, recovery of waste and final treatment and to turn it to less harmful waste and lastly to dispose of. To manage the BMW efficiently it is required to tackle it at its source (Chartier et al., 2014).

It has been estimated that only about 10% to 25% of BMW is unsafe and harmful while the remaining 75% to 95% of waste generated in the facility may be non-hazardous. The hazardous waste produced pose physical, chemical, microbiological health risk to the general population coming in contact or to the health-care workers associated with handling, treatment, and disposal of waste (Li et al., 1993).

The Ist edition of the World Health Organization (WHO) handbook on safe organization and management of wastes generated from various healthcare facilities is known as "The Blue Book", which was released in 1999. The second edition of "The Blue Book" was published in the year 2014, which incorporates new methods for safe disposal of Biomedical Waste and new measures for pollution control and their detection techniques. It also covers new topics such as the management of healthcare waste generated in accidents and emergencies; pandemic situations, drug-resistant bacteria, and climate changes (Chartier et al., 2014). With this brief introduction, this chapter deals with the types of waste, rules/standards of their management, safe disposal criteria, their impact on environment, advances in their disposal process.

2. INTERNATIONAL CONVENTIONS AND AGREEMENTS ON WASTE MANAGEMENT, ROLE AND PARTICIPATION OF INDIA

Various international agreements and conventions are made in the meantime to curb environmental pollution. Protocols that are particularly relevant to biomedical waste management, environmental protection, sustainable development, and future perspectives on environmental protection and rehabilitation should be kept in mind during the formulation of any waste management policies. Amongst these, the important is "Basel Convention on Hazardous Waste, Stockholm Convention on organic pollutants and Minamata Convention on Mercury". Basel Convention is the most inclusive of global treatment on hazardous and other types of wastes with 170 participating member countries. The objective of this is to protect human health and the environment against the adverse effects which result from the generation, segregation, and disposal of hazardous wastes. It includes clinical/anatomical and other types of waste from health care institutions such as hospitals, health centers, diagnostic facilities and clinics, biotechnology setups, and related waste generation locus (Krueger et al., 2001). Stockholm Convention on Persistent Organic Pollutants (POPs) is a global treaty to protect human health and the environment from POPs (like dioxins and furans). POPs are toxic chemicals that get accumulated in the lipid layers and fatty tissue of living organisms and can cause damage. POP chemicals are formed by medical waste incineration, combustion of waste, and other processes (Fiedler et al., 2007; Lallas et al., 2001). The guidelines on best available practice techniques and guidance on best environmental practices (BEP) were formed in the year 2006. BEP including a source of production reduction, segregation of harmful waste, recovery, and recycling, training in best-practice methods, and proper waste collection and transport and related processes and procedures are defined in the respective treaties and conventions (Draft, 2004). Minamata Convention on safe Mercury use is also given a global document that formulated directions and guidelines to protect human health and the environment from the adverse effects of mercury (Mackey et al., 2014). In 2014 more than 90 nations signed the first new global convention on environment and health in Japan. This treaty guides and asks to abide to phase out of certain medical equipment in health-care services, including mercury-containing medical items such as mercury thermometers and blood pressure devices using mercury (Khobragade, 2019). The WHO policy paper suggests that governments should adopt recycling, polyvinyl chloride free medical devices, risk assessment, and sustainable technologies for the promotion of environmentally safe management of BMW. India was amongst the pioneers to implement "Biomedical waste management rules in 1998 and later amended as a draft in 2003, 2011 under Environment Protection Act (EPA)". India is a signatory to an international legally binding and environmental treaty on POPs that aims to eliminate or decrease the production of POPs. "Biomedical waste management rules, 2016 under the provisions of Environment Protection Act, 1986" were notified by the "Ministry of Environment Forests and Climate Change, Government of India". These rules also fix up the lacuna in the earlier rules to regulate the disposal according to various categories of BMW ("Ministry of Environment and Forests Notification. Bio-Medical Waste (Management and Handling, 1998) Rules, New Delhi; Government of India Publications; 1998. p. 276‑84"). "Role and Responsibilities of Urban Local Bodies as per Bio-Medical waste Management Rule 2016" are provided under which, Schedule III, provides the list of Prescribed Authorities (Municipalities or Corporations, Urban Local Bodies and Gram Panchayats) and the Corresponding Duties. This schedule lists the duties of administration concerned with policymaking, issue of guidelines, an inspection of premises, land allocation, etc. Schedule IV provides

	label for BMW containers or bags
	label for transporting BMW containers or bags

This also provides forms to enter the information like Category, Sender's name, Contact person etc.

3. Risks from Biomedical Waste

3.1. Health Risks (Acc. to WHO Documents)

Health-care waste poses the potential risk of transmission of pathogens/microbes that can communicate a disease to patients, health care workers, and other livings that may come in contact by any means. Drug-resistant microorganisms are other potential hazards which may toxin into the environment thus extended from health care facilities (Mastorakis et al., 2010). Biomedical waste and by-products thereof may affect adversely directly to the associated people. Also, other indirect means of risk are described as follows:

- Sharps-inflicted injuries- the biomedical waste produced may contain sharps such as syringes, needles, any type of metallic non-metallic implants, surgical instrumentation generated waste, etc. that may cause injury to the health care workers, the patient, or others involved in patient care including those health care workers who are involved in the waste disposal and sanitation.
- Exposure to pharmaceutical products either toxic or dose-dependant toxicity, particularly antimicrobials and cytotoxic drugs released into the surroundings, and to chemical substances such as mercury or POPs and dioxins, during the handling or disposal including incineration of biomedical wastes; the waste thus produced may

pollute the nearby water bodies and land area or air and exposure to it may pose a health risk.

- Burns due to chemical exposure during disinfection, sterilization or waste treatment in the health care facilities;
- Air pollution results from the release of particular matter during surgical or therapeutic diagnostic procedures like electro or radio cautery and incineration process;
- Other thermal injuries occurring in conjunction with open burning and the operation of medical waste incinerators;
- Exposure to the radiation used in radiation units or during radioactive waste disposal.

3.2. Sharps-Related Injuries

WHO estimated that globally, about 16 billion injections are administered annually. Disposal of syringes always remains a tough task to handle, and not all are safely disposed of, creating an avoidable risk of injury and infection (Kumar et al., 2015).

Though the use of contaminated needles and syringes in low- and middle-income countries have reduced in recent years, especially due to efforts by the agencies involved to reduce and reuse of injection systems and encouraging the use of single-use devices. Despite satisfactory progress, in the year 2010 only, unsafe injection practices were still responsible for 33800 new HIV infections and 1.7 million hepatitis B and 315000 hepatitis C infections (Pepin et al., 2014).

Other hazards occur from waste scavenging at disposal sites by unauthorized workers and rag pickers and during the manual sorting and unscientific handling of hazardous biomedical waste generated from healthcare facilities. In many regions of the world, especially in low- and middle-income countries such practices are very common due to poverty and scarce information and administrative insufficiency. The waste handlers remain at immediate risk of needle-stick injuries, sharp injuries, and toxic or infectious material exposure as being directly involved in process of segregation and disposal (Mathur et al., 2012).

3.3. Environmental Impact of Biomedical Waste

Disposal including treatment of hazardous BMW may pose risks indirectly through pathogens and toxic pollutants released into the environment during disposal (Hiltz et al., 2007; Manzoor et al., 2019). Figure 2 represents the risk of BMW.

- Drinking, surface, and ground waters can be contaminated in case of release of untreated biomedical wastes in landfills or sewerage system. If landfills are not properly constructed and cordoned off it may lead to such contaminations.
- Chemical substances are released into the environment during treatment of health care wastes with chemical disinfectants, and if these substances are not handled,

stored and disposed in scientific and safe manner, it can lead to environmental hazards.

- Biomedical waste incineration is widely practised, but incineration inadequately or incineration of unsuitable and materials which are not mean to be incinerated results in the release of air pollutants and in the generation of ash residue that may also pollute land. Materials containing or chlorine treated materials can generate dioxins and furans, on incineration which are carcinogenic and have been associated with many adverse health effects including cardiorespiratory illnesses, heavy metals or materials with high metal content such as lead, mercury and cadmium can lead to the release of toxic metals in the environment if incinerated (Rahman and Singh 2019).

Image Source: Handbook of waste management, Municipal Corporation, Rohtak.

Figure 1. Risks of BMW to people vulnerable.

3.4. Bio-Medical Waste Management Rules, 2016. (Capoor et al., 2017)

Bio-medical Waste Management Rules, 2016 supplant old BMWM rules of 1998 and are in force with gazette notification by Government of India, Ministry Of Environment, Forest and Climate Change. The application of BMW rule 2016 is schematically shown in Figure 2.

These rules classify animal and biomedical waste and include and demarcate wastes thus generated. It also defines animal houses, authorities and authorised persons, biological and biomedical waste and its handling, treatment and disposal facilities (Sheth et al., 2017). T It also goes in sphere of accidental biomedical waste exposure hazards. Occupier responsibilities and operational management of biomedical waste generation, and management of BMW disposal topics are also dealt with in this act. It also enacts the authorities and regulating bodies responsible for the management of biomedical waste. The action plan for BMW management is described in Figure 3.

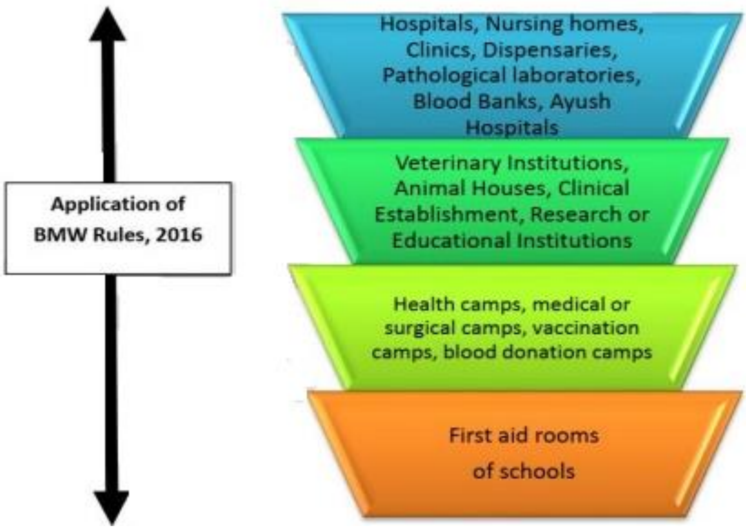


Image Source: Handbook of waste management, Municipal Corporation, Rohtak.

Figure 2. Schematic of Application of BMW Rules, 2016.

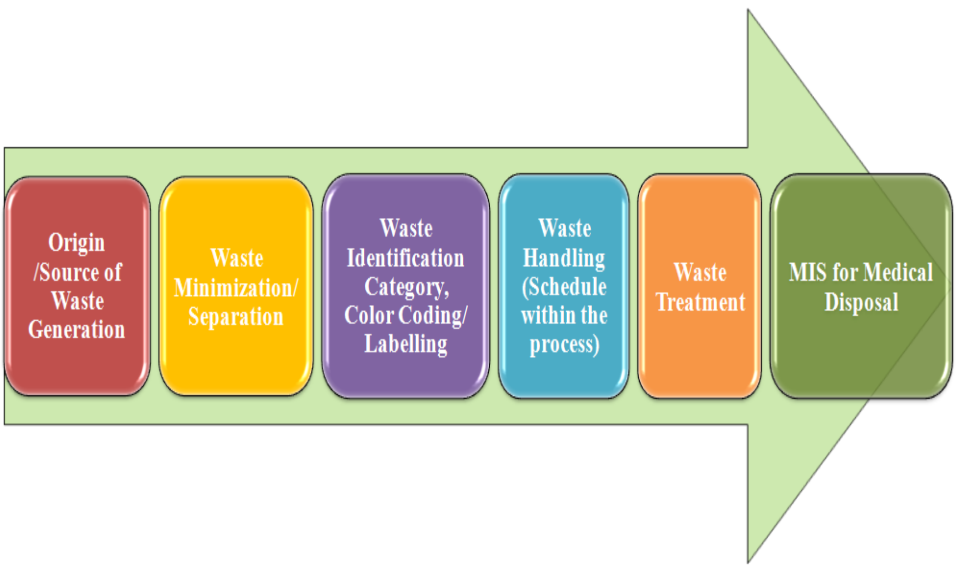
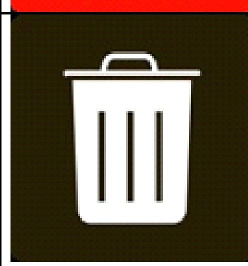


Figure 3. Action Plan for BMW management for their treatment and disposal.

4. Biomedical Waste (BMW) Classification and Categories

Medical waste is not liked by anyone, but it's unfortunate. The disposal process is very needed to done timely but to do this efficiently it is prior requirement to understand the facts of knowing what kind of waste. Typically, medical waste is classified into four different categories: infectious, hazardous, radioactive (Bhojak et al., (2021); Hegde et al., 2007; Sinha et al., 2020), and general, which are briefly described in Table 1.

Table 1. Description and types of bio-medical waste

Type	Description	Symbol
Infectious waste	Waste that has the possibility of causing infections to humans. It can include human or animal tissue (blood or other body parts), blood-soaked bandages, discarded surgical gloves, cultures, stocks, or swabs to inoculate cultures. Many waste streams in this category, including human or animal tissue, can also be labeled as pathological waste, which requires specific treatment methods.	
Hazardous waste	Waste that has the possibility to affect humans in non-infectious ways, but which meets federal guidelines for hazardous waste under the Resource Conservation and Recovery Act (RCRA). Hazardous waste includes chemicals, both medical and industrial. Some hazardous waste can also be considered infectious waste, depending on its origin and exposure to human or animal tissue prior to discard. Old drugs, including chemotherapy agents, are sometimes hazardous. Although not RCRA waste, sharps are hazardous in that they can cause injuries. Among waste managers, sharps are objects that can puncture or lacerate the skin; they include needles and syringes, discarded surgical instruments such as scalpels and lancets, culture dishes and other glassware.	
Radioactive waste:	It can be generated from nuclear medicine treatments, cancer therapies and medical equipment that uses radioactive isotopes. Pathological waste that is contaminated with radioactive material is usually treated as radioactive waste rather than infectious waste. Most hospitals generate radioactive waste as do some doctors' offices and veterinary offices if they offer brachytherapy.	
General waste	(Municipal Solid Waste): About 85% of waste generated at medical facilities is no different from general household or office waste, and includes paper, plastics, liquids and any other materials that do not fit into the previous three categories. Waste professionals refer to this as municipal solid waste, and it is usually disposed of in landfills.	

Further, the types of BMW, their segregation, collection treatment and processing ways are displayed in Table 2 as per Government of India Ministry of Environment, Forest and Climate Change Notification.

Table 2. BMW: Categories, Segregation, treatment/processing and disposal

Category	Type of Waste		Type of bag or container to be used		Treatment and disposal options
RED	Contaminated waste (Recyclable)			Non-chlorinated plastic bags /containers	Autoclaving or microwaving followed by shredding or mutilation.
WHITE TRANSLUCENT	Waste sharps including metals			Punch Proof/Liquid Proof/Tampe red Proof container	Autoclaving or dry heat sterilization followed by shredding or mutilation or encapsulation.
BLUE	Glasswares			Cardboard boxes with blue colored marking	Disinfection (by soaking the washed glass waste in sodium hypochlorite) or through autoclaving or microwaving and then sent for recycling.
	Metallic body implants				
YELLOW	Human and anatomical waste Soiled waste			Non-chlorinated plastic bags or containers	Incineration or plasma pyrolysis or deep burial. (In absence of above facilities, autoclaving or microwaving).
	Expired or discarded medicines: pharmaceutical waste like antibiotics, cytotoxic drugs.			Puncture proof, leak proof, tamper proof containers	Sent back to manufacturer or disposed by incineration. Cytotoxic drugs to be returned to the manufacturer or incineration at >1200°C /encapsulation/plasma pyrolysis at > 1200°C
	Chemical liquid waste: disinfectants, X-ray liquid, secretions, lab etc.			Yellow colored non-chlorinated plastic bags or containers	Pre-treat before mixing with other wastewater. The combined discharge shall conform to the discharge norms in schedule III.
	Discarded clothes/ beddings contaminated with blood or body fluid.			Yellow colored non-chlorinated plastic bags or containers Yellow colored containers or non-chlorinated plastic bags	Non-chlorinated chemical disinfection followed by incineration or plasma pyrolysis.
	Microbiology, biotechnology and other clinical laboratory waste				Pre-treat to sterilize with non-chlorinated chemicals on-site as per NACO or WHO guidelines thereafter for incineration.

For handling BMW, their segregation and encapsulation is required. After segregation of different types of BMW as mentioned above their encapsulation is done which involves filling of containers with defined waste using colour code mentioned above followed by adding of immobilising material (bituminous sand, cement mortar, or clay etc.) and their sealing. It is mainly used for pharmaceuticals and for incineration ashes with a high metal content. The containers are sealed and placed into landfill sites to prevent scavengers gaining access to it and prevention of percolation into groundwater (Chartier 2014). The measures for BMW management, disposal, and treatments must follow the Standards specified in Schedule-III which are emended time to time are briefly described as follows (Chand et al., 2020; Chitnis et al., 2005):

- Prior permission from the prescribed authority is required for disposal of different type of BMW by deep burial. The deep burial facility is allowed only in remote areas with no admission to any bio-medical waste treatment facility by individual or common as per the provisions and guiding principle issued by CPCB (Central Pollution Control Board). The plastic bags used for deep burial shall be as per Bureau of Indian Standard (BIS) and must be prevailed the Plastic Waste Management Rules.
- The disinfection process should be done using twenty minutes with a chemical mixture of at least 10% Sodium Hypochlorite and 30% residual chlorine or with any other chemical reagent that exhibit diminution in efficiency for microorganisms by $Log10^4$ of its prior value as given in Schedule-III.
- To prevent unauthorized reuse of any BMW, its mutilation or shredding must be done properly.
- Before incineration of BMW, no chemical pre-treatment is allowed excluding micro-biological, laboratory and highly infectious waste.
- Ash generated from incineration process of any BMW may also be hazardous therefore; their disposal should be through proper protocols. If such ashes may contain toxic/hazardous component beyond the limit prescribed by Hazardous Waste (Management, Handling and Transboundary Movement) Rules, 2008 then they must be decompose, treated or stored through standards method (Vivek et al., 2019).
- As per "Medical Termination of Pregnancy Act 1971" which is amended time to time, the dead Foetus below the viability period is comes under "human anatomical waste." This is handed to common bio-medical waste treatment operator and disposal facility which allows the disposal in yellow bag which prior requires the copy of the official "Medical Termination of Pregnancy certificate from the Obstetrician or the Medical Superintendent of hospital or healthcare establishment" (Patil et al., 2005).
- The used "cytotoxic drug vials" requires proper conscious disposal and otherwise can be hazardous. It must be sent back their Pharma-manufactures for proper disposal at single point and must not be supplied to any to unauthorised person under any circumstances. Other options may involve their incineration at common BMW treatment and disposal facility or TSDFs or plasma pyrolysis is at elevated temp. i.e., >1200°C (Stolar et al. 1983).
- Any type of residual/used/discarded chemical wastes like disinfectants and chemical sludge must be sent only to the operator of common BMW treatment and disposal facility for their proper disposing at hazardous waste treatment, storage and disposal facility.
- The Guidelines of World Health or National AIDS Control Organisation must be properly followed for pre-treatment like disinfection or sterilization of on-site lab

waste, micro-biological waste, blood/plasma samples, blood bags, syringes, etc. before transferring them to the common BMW treatment and disposal facility.

- If there is no common BMW treatment and disposal facility nearby then the incinerator facility may be installed by the occupier after taking authorisation from the "State Pollution Control Board." However, no in-house incinerator facility is allowed otherwise.
- After being used, syringes should be either mutilated or needles should be cut and or stored in tamper proof/leak proof/puncture proof containers for sharps storage.
- Wherever there is no common BMW treatment and disposal facility nearby or occupier is not linked with it then it is the responsibility of occupier to sterilize and dispose the BMW waste in the prescribed manner.
- During household healthcare activities, the generated BMW shall be segregated as per these rules and handed over to municipal waste collectors in a separate bags/containers. It is the duty of the urban local bodies to ensure their proper disposal and for this they must have to tie-up with the common BMW treatment and disposal facility to pick-up this waste from the Material Recovery Facility (MRF) or from the house hold directly, for their final disposal in the prescribed manner as per this Schedule.

5. Treatment/Disposal of Bio-Medical Wastes (BMW) (Capoor et al., 2017; Datta et al., 2018; Mathur et al., 2012)

5.1. BMW Treatment Using Incineration (Glasser et al., 1991)

Under a controlled combustion process, a thermal treatment technique is used for disposal of BMW with the primary objective of reduction of volume and energy recovery from the waste stream. It is the most followed waste to energy (WTE) technique that involves the recovery of heat produced from combustion and its conversion to electric power. The waste generated has both components i.e., organic and inorganic: the heat is combusted and produced from organic components while whereas inorganic components contributes to formation of ash (Gautam et al., 2010). The steps of incineration process as shown in Figure 4. All incinerators shall meet the following operating and emission *Standards for Incineration.*

5.1.1. Operating Standards

The Combustion efficiency (CE) is related to average concentration of carbon dioxide (CO_2) and carbon monoxide (CO) gas produced in the incinerator exhaust and calculated using the eq. 1:

$$CE = \frac{\% CO_2}{\% CO_2 + \% CO} x100 \qquad (1)$$

and must be at least 99.00%. The incineration involves step heating in two chambers: primary chambers with minimum temperature up to 800°C, while the secondary chamber minimum temperature of 1050°C ±50°C. The gas residence time of secondary chamber shall be ~ 2 Sec.

5.1.2. Emission Standards

Parameter	Standards	
	Limiting concentration ($mgNm^3$) unless stated	Sampling Duration in minutes, unless stated
Particulate matter	50	30 or 1 Nm^3 of sample volume, whichever is more
NO and NO_2	400	30 for online sampling or grab sample
HCl	50	30 or 1 Nm^3 of sample volume, whichever is more
Total Dioxins and Furans	0.1ng TEQ/Nm^3 (at 11% of O_2)	8 hours or 5Nm^3 of sample volume, whichever is more
Hg and its compounds	0.05	2 hours or 1NM3 of sample volume, whichever is more

5.1.3. Stack Height

In accordance with the "Central Pollution Control Board Guidelines of Emission Regulation Part-III" and "Environment (Protection) Act, 1986," the general parameters shall meet the essential requirement of monitoring which defines the minimum stack height is 30 meters above the ground.

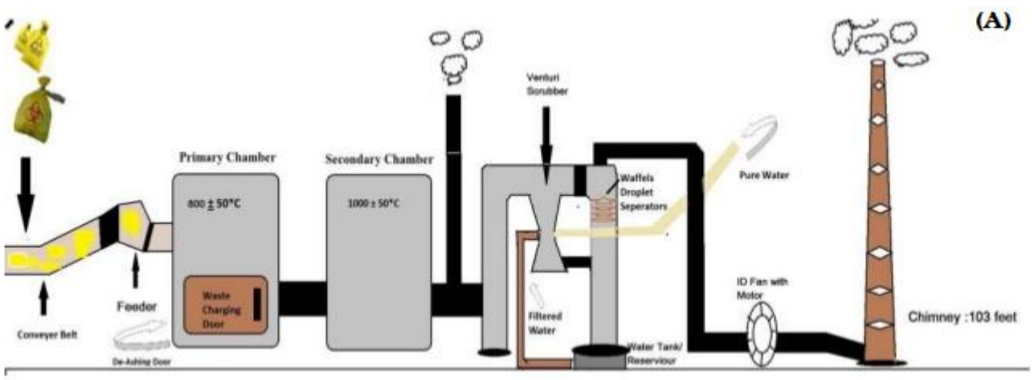


Image Source: Published in 2013, *An Optimal Design of Hazardous (Biomedical) Waste Incineration Plants.* Ref: Wahid and Katoch.

Figure 4(A). Schematic of double chambered incinerator for BMW management.

Further measures for maintaining incinerations are:

- Within the period of 2 years from the date of notification, the existing incinerators shall meet the above standard terms and conditions and must comply "Standards for Dioxins and Furans of 0.1ngTEQ/Nm." Further, all forthcoming or captive incinerator facility shall also comply with standards these standards.
- In order to achieve the emission limit from incinerator, the existing secondary combustion chambers and pollution control devices shall be properly retrofitted.

- Before incineration, waste shall not be chemically treated with any chlorine based disinfectants.
- The collected BMW based incineration ash shall be disposed off at common hazardous waste treatment and disposal facility. They may be disposed at municipal landfill, if they contain toxic metals within the regulatory quantities as defined under the "Hazardous Waste (Management and Handling and Transboundary Movement) Rules, 2008" amended time to time.
- The incinerator fuel shall contain low sulphur amount viz. Light Diesel Oil, Compressed Natural Gas, Liquefied Natural/Petroleum Gas.
- The gas emission should be checked once in three months by the occupier or operator of a common BMW treatment and disposal facility under optimum capacity of the incinerator through a approved labs under the "Environment Protection Act, 1986." The record of reports analysis shall be maintained and submitted to the prescribed authority. Such monitoring are desired once in a year for maintaining standards of dioxins and furans.
- Further, continuous gas emission must also be monitored as per parameters stipulated by "State Pollution Control Board or Pollution Control Committees" and recorded real time data shall also be submitted to the authorized committee by the occupier or operator of the common BMW treatment and disposal facility
- All monitored values shall be calibrated and corrected to 11% Oxygen on dry basis.
- The combustion gas analyzer to measure CO_2, CO and O_2 must be installed and managed by occupier/operator of a common BMW incinerator. Further, the temperature, retention time and turbulence of incinerators combustion chamber should be maintained in such a manner so as to obtain slag and bottom ashes with total organic carbon content > 3% or > 5% by wt. of their loss on ignition.

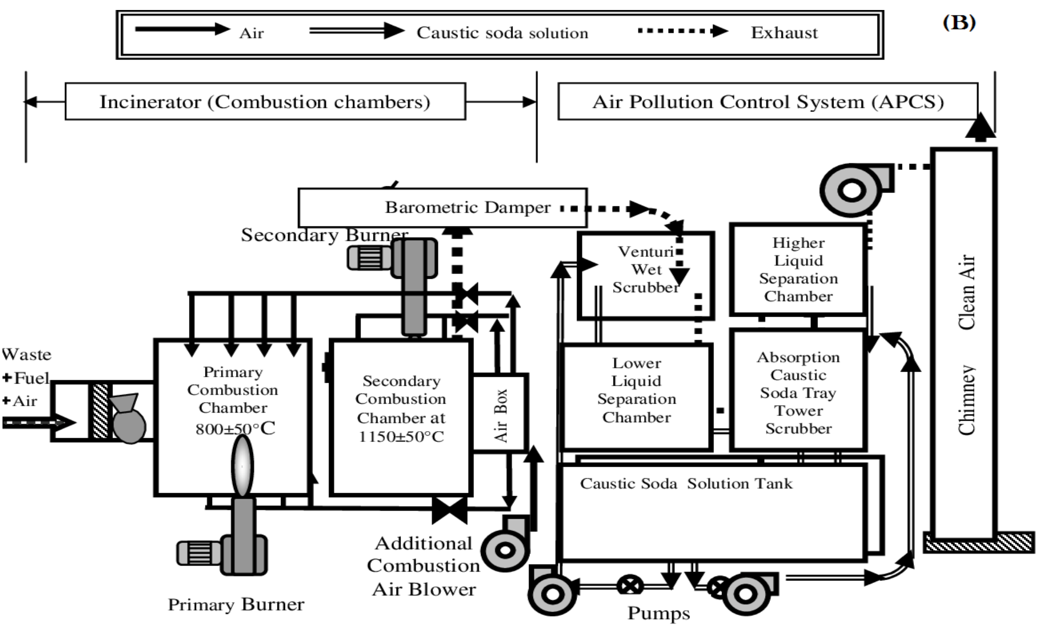


Figure 4(B). Block diagram of double chambered incinerator for BMW management.

5.2. BMW Treatment Using Plasma Pyrolysis

Plasma Pyrolysis (Nema and Ganeshprasad 2002) utilizes very high temperature to dissociate waste; this is done in the absence of oxygen environment. It is also known as non-incineration thermal process. Graphite electrodes are used to generate plasma arc which helps to convert electrical energy into heat with efficiency >90%. This technology is used for variety of waste management which includes safe disposal of any kind of organic wastes viz. municipal solid waste, BMW, hazardous waste, etc. The products obtained after plasma Pyrolysis technique can be further disposed-off or reuse after converting them to value aided product (Stringer, et al., 2010; Capoor and Bhowmik 2017; Huang et al., 2003). Figure 5 represents the block as well as schematic diagram for plasma pyrolysis BMW treatment plant.

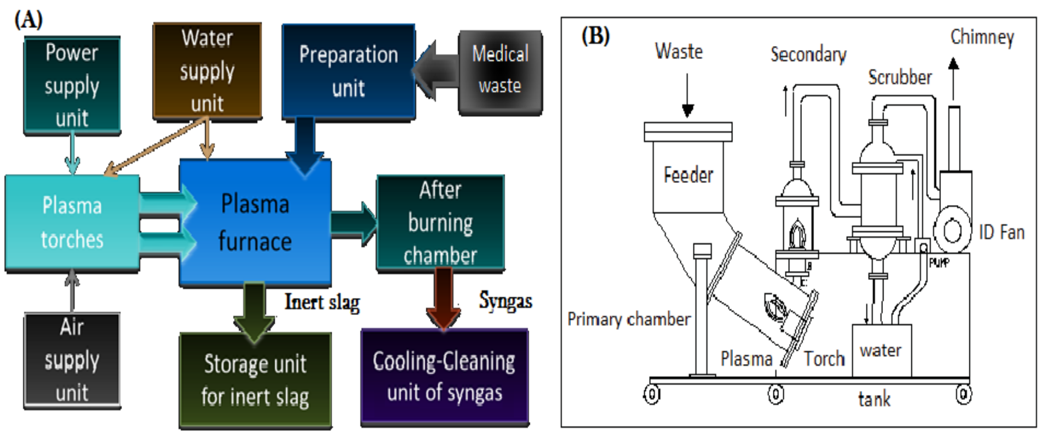


Figure 5(A). Block diagram (B) Schematic of Plasma Pyrolysis unit for BMW treatment.

5.2.1. Operating and Emission Standards

The Combustion efficiency (CE) is related to average concentration of carbon dioxide (CO_2) and carbon monoxide (CO) gas produced in the plasma gasification exhaust and calculated using the same equation 1 as used for CE calculation for incinerator. The combustion chamber temperature after plasma gasification shall be 1050°C ±50°C with gas residence time ~ 2 Sec. The necessary monitoring facilities should be attached to the stack and stack height shall be 30meters above ground level with at least 3% oxygen in the stack gas.

5.2.2. Standards/Measures for Air Emission/Air Pollution Control/Ash disposal

- The Plasma Pyrolysis/Gasification follow the same emission standards as that for incineration.
- Air pollution control device suitably designed Plasma Pyrolysis/Gasification may be installed if required maintaining prescribed emission limits.
- Chemical pre-treatment of BMW with any chlorinated disinfectants/chlorinated plastics must be avoided before Plasma Pyrolysis/Gasification.
- “Hazardous Waste (Management, Handling and Transboundary Movement) Rules 2008” must be followed for disposal of produced ash or vitrified material from BMW after Plasma Pyrolysis/Gasification.

5.3. BMW Treatment Using Autoclaving (Myneedu et al., 2020)

Autoclaving is the technique that utilizes high pressure to generate steam. This a physical method of sterilization through heat used to kill bacteria/viruses/spores present in waste. It is also known as a steam sterilizer. It is very commonly used for healthcare and industries for different purposes. It operates at particular temperature to generate steam for a defined incubation time. This is considered as one of the most effective, efficient with low operational cost and environmentally sustainable method of sterilization as it is based on moist heat sterilization without generation of any harmful effluent except water. Thus, used very often for sterilization as well as disinfection/treatment of BMW in hospitals. Figure 6 represent the schematic and realistic autoclave unit for BMW treatment.

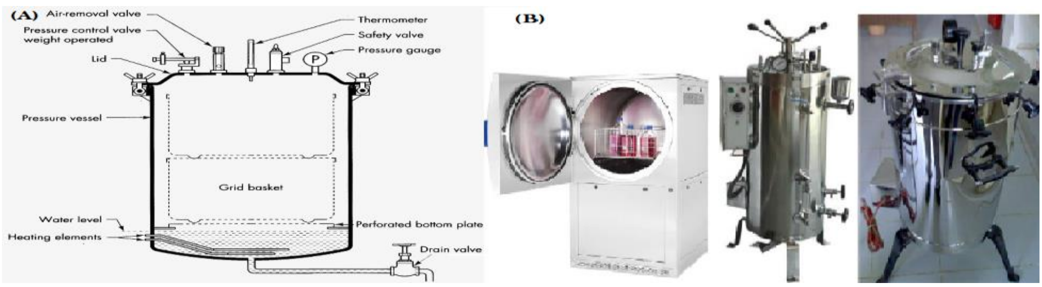


Figure 6 (A) Schematic of Autoclave (B) Realistic autoclaves: different size and shapes according to BMW management facility size and requirements. “pharmawiki, https://ilabot.blogspot.com.”

5.3.1. Standards/Measures for Autoclaving

- For operation of gravity-flow autoclave to treat BMW for
  a. 60 minutes residence time: temperature of ~120°C with 15 pounds per square inch (psi) pressure is required.
  b. 45 minutes residence time: temperature of ~135°C with 31 psi pressure is required.
  c. 30 minutes residence time: temperature of ~149°C with 52 psi pressure is required.

Thus lower the residence time, higher operating conditions of temperature and pressure is required.

- For operation of vacuum autoclave to treat BMW, the medical waste is first subjected to rough vacuum to purge out air from autoclave. The air exit from removed during this cycle can be toxic/infectious, may contain pathogen so is required to disinfected using High Efficiency Particulate Absolute (HEPA) filters, activated carbon (AC) filtration, steam treatment, etc. to prevent release of. After pre-vacuum stage, the slurry of waste is subjected for different autoclaving conditions depending their residence time, which is less as compared to that for gravity based autoclave.
  a. 45 minutes residence time: temperature of ~121°C with 15 psi pressure is required.

b. 30 minutes residence time: temperature of ~135°C with 31 psi pressure is required

- As BMW is infectious/toxic/hazardous, therefore, its proper dissociation/ decomposition will be ensured only if conditions of autoclaving like time, temperature and pressure will complete. In case due to any reasons if autoclaving is failed to achieve the pre-mentioned condition then entire load of BMW must be autoclaved again till its completion.
- The entire length of the autoclaving cycle must be recorded to ensure proper decomposition of BMW. For this purpose, recording device with computer/graphic interface is attached with autoclave which automatically records the date/time/load identification number/operating parameters for its continuous monitoring.
- For proper decomposition of any pathogens/inactivation of spores present in BMW, the Validation test is required for optimization of autoclave credentials. The validation test uses 4 biological indicator strips: 1 is used as a control and left at room temperature and other 3 three strips are placed approximately in centre of 3 chambers of autoclave along with waste. The proper measures like use of PPE (Personal protective equipment) like gloves/face mask/coveralls should be followed to open the autoclave containers in order to these biological indicator strips. The occupier or operator of BMW treatment/disposal facility must conduct such validation test at least 3 consecutive times to optimize the operating conditions of autoclave. The optimized conditions (temperature, pressure and residence time) for autoclave is defined when all 3 biological indicator strips/vials show complete inactivation of the spores present in BMW. Further, such optimization must be done via this validation test once in 3 months.
- Other than validation test, routine test is also done for optimization of autoclave functioning. For this purpose, a chemical indicator strip or tape is used. The change in colour of this chemical strip is used to verify that autoclave reached at certain operating temperature. Sometimes, it may require placing more than 1 strip over different locations of waste to ensure their proper autoclaving. This routine test must be done by the occupier/operator of BMW treatment facility for each batch of waste to maintain the records.
- In order to govern the complete autoclaving of spores i.e., to complete ensure the disinfection of spore a biological indicator is used. This is called Spore testing to completely and consistently killing of the pathogens/spores. This biological indicator for autoclave is a vials or spore Strips of "*Geobacillus stearothermophilus*; with at least 1X106 spores," which is autoclaved with operating conditions of 30 minute residence time having 121°C temp. and 15 psi pressure. Such spore test must be done by occupier/operator of BMW treatment and disposal facility at least once in a week and maintained the record.

5.4. BMW Management Using Microwaving (Myneedu Et Al., 2020)

Another non-incineration method for sterilizing hospital and BMW waste is Microwaving. For this purpose Microwave radiation (2.45 GHz, at a power of 3 kW, high pressure of 7atm) are generally used. Figure 7 represent the image of Sterile Microwave that is generally used in various BMW treatment and disposal facility. The BMW are shredded and moisturized before applying for microwave sterilization. Typically, it consists of three reactor units: (a) Microwave Solid Disposal Unit; (b) Microwave Cracker; and (c) Microwave Oxidation Unit. The first unit is used to annihilate liquid and solid BMW. The solid BMW is fed from the top of the reactor and is allowed to partially oxidize by air followed by microwave pyrolysis. After decomposition, the produced gas and tar is allowed to enter in 2nd unit of reactor i.e., microwave cracker which produce hydrocarbon gases from decomposed products which are allowed further to oxidised completely by 3rd unit i.e., microwave oxidizer. So that at the microwave oxidizer exhaust no air pollutants (nitrogen oxides (NOx) and volatile organic compounds (VOCs)) are present. By this process, the collected disposal is obtained which has been reduced to ~95% of its original volume thus, become cost effective to dispose off. Thus, microwaving of BMW provides safe, easy, economical, fast and on-site process which includes pyrolzing, cracking and oxidizing with no air pollutant generation, the only by product is ash that may be disposed in a landfill.

Image Source: Bertin medical waste co. microwave sterliwave 100.

Figure 7. Sterile Microwave for BMW treatment.

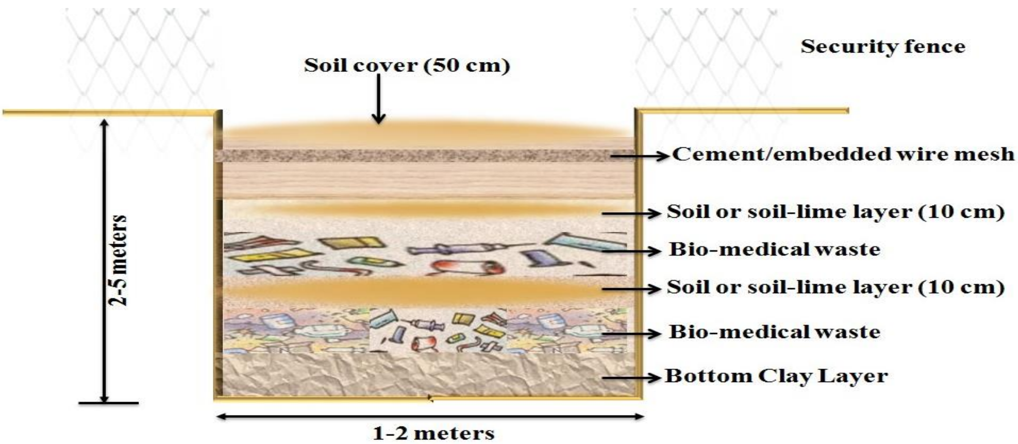
5.4.1. Standards/Measures of Microwaving

- For BMW like cytotoxic, hazardous/radioactive wastes, contaminated animal carcasses, body parts and large metal items microwave treatment shall not be used.
- The regular efficacy test or routine tests shall be done for microwave system. The performance guarantee must be supplied by the supplier i.e., completely and consistently killing of the bacteria and other pathogenic organisms. There must be approved biological indicator at the maximum design capacity for each microwave unit.

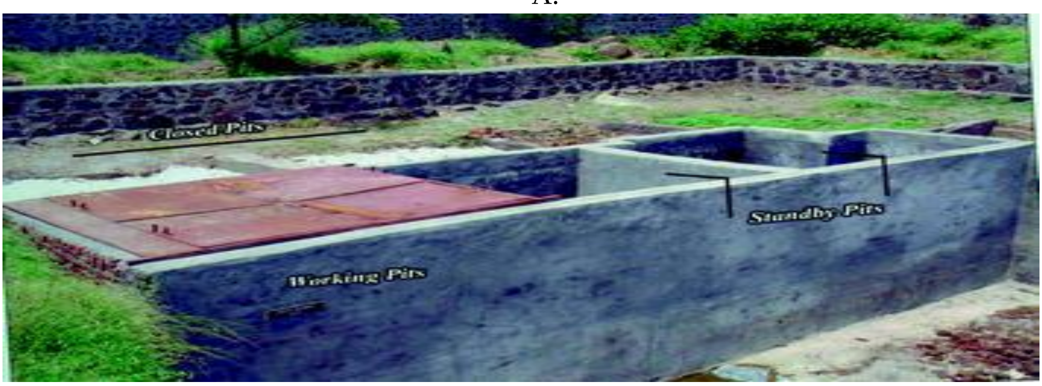
- For this purpose, *Bacillus atrophaeus* spores based biological indicators strips shall be used at least 1 x 104 spores detachable strip, which has to be placed with waste and exposed to same conditions as the waste during a normal treatment cycle.

5.5. BMW Management/Disposal Using Deep Burial

Deep Burial is a physical method of BMW management/treatment and disposal, for this purpose, 2 meter deep pit or trench is needed to be dug out. Waste is dumped in this pit up to half filled only followed by its covering with lime within 50 cm of the surface and then filling the rest of the pit with soil. Figure 8 represents the image of real deep burial for management/treatment/disposal of BMW.



A.



B.

Image Source: https://media.springernature.com/original/springer.

Figure 8. A. Schematic of Deep Burial BMW management/disposal. B. Deep Burial BMW management/disposal.

5.5.1. Standards/Measures of Deep Burial

- As deep burial contains hazardous/toxic components therefore it must be ensured that it must be far from any habitats/living or other reachable places so that animals do not have any access to burial sites and no contamination occurs to surface water or ground water.
- For this purpose proper fencing using galvanised iron or wire meshes covers may be used. On adding new cycle of waste into a pit, a soil layer of 10 cm shall be added to cover it.
- The process of burial must be carried under close and dedicated supervision. Further, there should not be any relatively impermeable and no shallow well close to the burial site.
- The ground water table level should be a minimum of six meters below the lower level of deep burial pit.
- It must be ensure before pitting that choose area should not be prone to flooding or erosion. It is also required to take permission for pit the deep burial from prescribed authority.
- The record of all pits used for deep burial must be maintained by the owner of BMW treatment/disposal facility.

6. ADVANCES IN WASTE MANAGEMENT (GAHLOT ET AL., 2019)

With the increase of waste generation and problem of not properly managing it, the focal challenge that the Human race is facing these days is related to protection of our ecosystem. Therefore, new advancements are coming in day by day and are very effective for managing waste to save our environment and surroundings. These advance method and technology is also found very promising for BMW management. Some of them are described as follows:

- Ozone (O_3) being a strong oxidizer it breaks down to a more stable form oxygen (O_2). It can be used for waste of pharmaceutical Industries, water based waste and environmental air pollution. Ozone based technology require waste shredders and mechanical mixers to facilitate exposure of the waste to the ozone and bactericidal agents. Regular quality tests are needed to keep standard with the microbial inactivation as per the existing laws (Stringer et al., 2010).
- Promession uses liquid nitrogen (cryo-drying) for freeze drying and mechanical straining consequently to disintegrate and make smallest of disposable particles of biomedical waste including human cadaver, anatomical waste before burial., This process speeds up decomposition due to small particle size. Both mass and volume are reduced. It also facilitates the recovery of the metals or any other valuable components present in the waste as dental fillings, orthopedic and orthotic implants and other materials of the waste (Stringer et al., 2010).
- Alkaline hydrolysis converts anatomical waste, gross pathology and other histopathology specimens, cadavers (dead bodies) into a decontaminated aqueous solution and chemical fixatives in such specimen or cadavers are destroyed.

Hazardous chemicals and waste contaminated by prions and other materials are also treated by alkaline hydrolysis. The waste is kept in the baskets or boxes and dipped into the hermetically sealed tank. Strong alkaline chemicals are added to the tank. Water at temperature of 127°C or higher (superheated water) is added and mixed and stirred with mechanical arms. Digestion of organic material takes 6–8 hours, by-products including mineral constituents of bones and teeth, amino acid solutions, sugars, soaps and salts are formed. Chemotherapeutic and cytotoxic agents are also disoposed and managed by this process. Aldehydes (such as formaldehyde and glutaraldehyde) are commonly used in health care waste management (Capoor and Bhowmik 2017).

- Membrane Bioreactors (MBR) combines the biologically activated sludge process with a membrane filtration as in reverse osmosis system for sludge and water separation. Various membrane bioreactor such as microbiological MBR as aerobic and anaerobic MBR, organic pollutant MBR are available and are used in industry (Alrhmoun 2014).

Newer and emerging technologies are in pipelines for management or disposal of BMW include Fe-TAML/peroxide treatment for pharmaceutical wastes, chemical reduction, supercritical water oxidation, base-catalysed decomposition, sodium reduction technique, superheated water steam process, sonic sanitization and destruction technology, biodegradation or bio-decomposition using certain bacteria that can digest plastics, mechano-chemical and electrochemical techniques, and phytotechnology. Though these technologies are not ready to be used as routine in health care waste disposal but are now under research for efficacy, efficiency and economy (Rubin and Burhan 2006).

7. Nanotechnology for BMW Management

Nanotechnology is the manipulation of matter at the nano scale (Bhattacharyya et al., 2009). As it is well known facts now that "nanomaterials exhibit unexpected properties compared to their bulk counterparts; their high surface-area-to-volume ratio imparts unique physiochemical properties, including versatile functionalities and enhanced reactivity or selectivity." These days *Nanotechnology* is used to improve quality of indoor air and to cleanse environmental air. Other uses may be in surface water cleansing and waste management. A photo catalyst is used with broad spectrum of visible or invisible light which is bactericidal and fungicidal. Various nano-technological techniques can be employed, and through various processes quality of air and water is managed. It utilize the light energy to generate free hydroxyl species and various superoxide anion (O^{2-}) that can oxidise and decompose highly toxic pollutants to less harmful and less toxic compounds like carbon dioxide and water or other inert substances or chemicals (Paramashivaiah et al., 2016). *Nano-photocatalysis,* is emerging as a novel technology. It is also used for "disinfection and decontamination" of health care waste water. As name suggest such catalysts are nano-sized thus provides enhanced surface reactivity and uses optical photon to generate energy.

Thus, utilizes our natural source i.e., solar energy or ultraviolet radiation to disinfect microbes. Such nanoparticles are also used to decontaminate antibiotic present in waste water. It is a cost effective technology with good efficiency and promising results (Alrhmoun 2014). Some recent work related to use of nano-photo-catalysis for BMW management are as follows:

- Badawy et al. (2014) modified photo catalytic activity of TiO_2 doped with Ag nanoparticles and studied their photo-catalytic behavior towards "degradation of pharmaceutical compounds commonly present in hospital wastewater."
- Meng et al. (2015) did TiO_2 nanosisal-like coating on cancer detecting nano-biochips for their disposal. These chips are employed in detecting diseases owing to their low cost, portable and sensitive features but hard to dispose.
- Sakir et al. (2016) synthesized ZnO and La doped ZnO nanoparticles by modified gel-combustion method. They observed increase bio catalytic properties of ZnO nanoparticles after doping with La towards different cell lines and PCM drug. They proposed La doped ZnO nanoparticles for hospital waste water treatment.
- Sulek et al. (2019) prepared photocatalytic TiO_2 based (metello) porphyrins hybrid nanomaterials. They tested catalytic activity of prepared nanoparticles toward the degradation of 4-chlorophenol and tramadol. They also observed considerable antibacterial activity of prepared nanoparticles against "Gram-negative (E. coli) and Gram-positive (S. aureus)" and thus propsed their use for the inactivation of microorganisms.
- Thiruppathi et al. (2019) hydrothermally synthesized CuWO4 nanoparticles (NPs) which were highly spherical and porous in nature. The optical band gap of CuWO4 NPs was found to be 2.12 eV and showed photocatalytic activity towards decomposition of diclofenac sodium (DFS) (medical waste) in the aqueous medium.
- Ahmad et al. (2020) synthesized Fe_2O_3 nanoparticles using Tamarix aphylla extract by a simple route. This extract acted both as "reducing and capping agent." They found crystalline nature of prepared Fe_2O_3 nanoparticles and found exceptional "antimicrobial activity against pathogenic multidrug resistant bacterial strains."
- Ansari et al. (2020) synthesized TiO_2 nanofibers (NFs) using sol-gel and electrospinning methods. Synthesized nanofibers showed "antibacterial and antibiofilm activity against Gram-negative Pseudomonas aeruginosa and Gram-positive methicillin-resistant Staphylococcusaureus (MRSA)."

BMW is hazardous as well as toxic thus cause infection to medical specialists, patients as well environment therefore proper management, treatment and disposal is required (Hooshmand et al. 2020). Photo-catalysis is gaining attention for BMW management and other environmental pollutants. Different types of photo-catalysts (TiO_2, ZnO, CdS, ZnS etc.) have been used for the treatment of various medical and environmental pollutants. Photocatalysts are used as both powders and thin films according to the requirement. Mainly TiO_2 and ZnO are most popular among all these photo-catalysts because of their high stability, low cost and environmental friendliness.

Conclusion

In this article, we have discussed different types of biomedical waste, their segregation, treatment and disposal. Rules and regulation to mange BMW under WHO and other government guidelines have been briefly described. Further, risks and handling of different types of waste, different treatment process has been descriptively mentioned to aware the readers those did not belong to health care facility directly. Some standards/measures of BMW through different types of treatment methods are described to generate the layman understanding. In order to introduce the concept of sustainable development in health care facility and BMW management, we should avoid the overuse of plastic in health care facility. We should imply the concept of 3Rs in BMW management/treatment and disposal. Also, new advances like use of various types of nanoparticles must be used for safe fumigate rather than use of chlorine based disinfectant. Also, use of nano-photo-catalysts for waste water treatment of hospitals and other health care units BMW management facility has been explore.

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Chapter 17

WATER POLLUTION AND ITS TREATMENT: FROM CONVENTIONAL TO NOVEL METHODS

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ABSTRACT

Availability of safe drinking water has become one of the major challenges for the mankind. Though the technical advances are not yet able to synthesize water economically yet the technology comes handy when we think of removal of pollutants from water. A number of pollutants are present in water and their chemical nature depends on their sources. Accordingly, varieties of methods have been developed for the removal of pollutants from water. These include the conventional methods viz. distillation, membrane filtration, chemical precipitation, coagulation, precipitation, oxidation, ion exchange and reverse osmosis, enzyme treatment and microbial degradation. Due to diversified nature of the pollutants, each of these methods has its own limitations.The development of novel technologies based on nanomaterials such as nanocellulose, graphene coated nanofilters, and carbon nanotubes promise more viable, economical and efficient solution for the water pollution in more than one way. These can be used as nanofilters, nanoadsorbents with modified and enhanced properties. In comparison to conventional methods, the nanofilters have greater advantages like these need less pressure to pass water through filters, have large surface area, have higher efficiency, and can be easilycleaned by back flushing method. Similarly, Nanoadsorbents also have great advantages like they have high specific surface area for adsorption and have high adsorption rate which can be implicated for removal of various contaminants like heavy metal, organic materials and bacteria from waste water.

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1. INTRODUCTION

Water is an importance resource responsible for origin of life on earth and its sustenance. Water is useful not only for drinking but also for a number of domestic works such as cleaning, cooking, bathing etc. Is equally used for industrial purposes, agriculture and recreation activities. About 70% of human body consists of water. Even 30-40% of bone mass comprises of water.Water is responsible for some of the vital functions in the human body. It is responsible for absorption of oxygen at alveoli, control of body temperature and digestion in intestine and excretion in kidneys. Also, it is the chief component of blood. The importance of water in human body becomes clear by the fact that just10% alteration in the body content leads to health problem and alteration of 20% body content of water results into death.

Primafacie it appears that earth has a plenty of water as about 71% of its surface is covered with water. But, it is the hard reality that most of this water is salty and cannot be used for drinking purposes. Approximately, 97% of the earth water is salt water so only 3% of it, which is fresh water, left for the humans, plants and animals. Adding to misery, two-third of the fresh water is present in the form of polar ice caps and only one-third is available for our use. The ready to use fresh water comes from surface and ground water. The various sources of surface water include ponds, rivers, lakes and streams whereas; ground water includes the seepage that collects in between rocks and soils underground. Statistically, the world's total water supply is of about 332.5 million $mile^3$ out of which over 96 percent is salty. Of total fresh water, over 68% is locked up in ice and glaciers. Another 30% of fresh water is underground water so only 3% of fresh water is available for the use of humans, animals and plants. In short, less than 1% of the earth water is available for drinking. Hope, now all of us will agree on the point that the water is a precious and limited resource which must be preserved and procured to ensure the sustenance of the life on earth.

Though it’s an imperative resource for the survival yet a number of anthropogenic and natural activities are responsible for water pollution. Getting clean and fresh water is one of the major concerns for the majority of the society. The polluted water has deteriorating effect not only on human health but also on the environment. A number of deadly diseases are caused by intake of polluted water. These include cholera, jaundice, tuberculosis, dysentery, diarrhoea, etc. The water pollution is not only a major problem in the global context but also a leading cause of deaths and diseases worldwide. As per one study, the water pollution accounts for the deaths of more than 14000 people daily. More than 1000 children die of diarrhea everyday in India. At least 90% of the China’s cities suffer from some form of water pollution and about 500 million people have no access to safe drinking water there in China.

Water pollution is a big threat not only to the developing countries but also to the developed countries like USA. The recent report on water quality in USA suggests that 45 percent of assessed stream miles,47% of assessed lake acres and 32 percent of assessed bay are classified as polluted. Ever-increasing demand for water and its fast dying sources have compelled the society and the governments to think and act seriously on water pollution.

A number of anthropogenic activities lead to water pollution such as mining, direct discharge of municipal solid waste, industrial wastes, agriculture waste, radioactive chemicals, and heavy metals, etc into the water bodies without significant recycling. Besides, natural activities viz. landslide, flood etc also lead to water pollution.

The conventional methods of wastewater treatment include the removal of solid, organic waste through various physical, chemical, and biological techniques. The primary, secondary, and tertiary levels of treatment of the effluents are followed by disinfection of water with various chemicals viz. the chlorine. The conventional methods have the limitations such as highly specific, poor treatment efficiency and high investment cost. These limitations have compelled the researchers to venture in the field of latest technologies viz. nanotechnology for the efficient, cost effective and better solution of water pollution.

This chapter is an approach to describe the various sources of water pollution, to discuss the conventional and novel methods used for the removal of various pollutants from water and merits of the novel methods over traditional methods.

2. Water Pollution

Water pollution can be defined as contamination of streams, lakes, seas, underground water by some harmful substances. Mainly water pollution occurs when unwanted material enters in to water, and changes its chemical, physical and biological properties. Water is an important natural resource used for drinking and other various purposes. (Haseena et al., 2017). The World Health Organization (WHO) says that polluted water is water whose composition has been changed to the extent that it is unusable.

So, this type toxic water, cannot be used for drinking purpose and also for agriculture, because it causes various diseases like diarrhoea, cholera, dysentery, typhoid and poliomyelitis, these diseases kill more than 500,000 people of world every year.

2.1. Sources of Water Pollution

There are various sources which pollute water bodies and are harmful for living species. These pollutants are listed below:

1. Natural sources for pollution
2. Sewage pollutants (Domestic and Municipal waste)
3. Suspended Solids
4. Agricultural waste
5. Industrial waste
6. Nutrient’s enhancement
7. Oil spillage
8. The disruption of sediments

2.1.1. Natural Sources for Pollution

Various natural incidents occur on earth which pollutes water. Some of these are given below.

1. Heavy rain fall
2. Atmosphere (dust particles)

3. Aquatic animals
4. Underground rocks
5. Surrounding Vegetation

Rain fall is the main cause of water pollution because it takes all the impurities like dust particles and oxides of sulfur and nitrogen present in air and comes on earth and pollutes water is main cause of water pollution, because due to acid rain sulfur dioxide (SO_2) and nitrogen oxides are emitted into the atmosphere and transported by wind and air currents. The SO_2 and NO_x react with water, oxygen and other chemicals to form sulfuric and nitric acids. These then mix with water and other materials before falling to the ground. As a result, it falls as the rain with lower pH than the normal. This acid rain gets mixed with ground water, thus polluting the later (Sivaramanan, 2015).

Dust particles pollute whole ground water, if dust from coal, petroleum or other similar materials falls onto a pool and river, the dust particles can settle down top surface of water and pollute water because these materials are hydrophobic, they do not mix well with water. By Adding surfactants- surface acting agents the surface tension of the water is reduced (Farhadloo et al., 2016).

The falling of leave and some other vegetative parts also cause water pollution.

2.1.2. Sewage Pollutants (Domestic and Municipal Waste)

Sewage pollutants includes garbage, shops and home waste material, detergents, food waste, cloths and some plastic materials. All of these are responsible for water pollution. In the sewage material, pathogen microorganism (bacteria, algae, fungi, protozoan) are developed and these microorganism cause water pollutions. If any animals or human drinks this water so these microorganisms enter the living organism body and cause many diseases (like typhoid, cholera, gastroenteritis, polio, viral hepatitis and dysentery) (Singh et al., 2020).These organisms are responsible for deoxygenation of water bodies which cause harmful effect on aquatic animals. Chemical fertilizers used by farmers also add nutrients to the soil, and this goes to rivers and seas and add to the fertilizing effect to the sewages.

2.1.3. Suspended Solids

Suspended solids are usually the waste material from industry and municipal outlets. These include sand and material at washing steps, organic content and suspended solids in the wastewater.

2.1.4. Agriculture Waste

Agricultural wastes originate from run-off cultivates areas and farms. The farmers usually use fertilizers and pesticides viz. DDT, dieldrin, aldrin, malathion, carbaryl etc. to kill insects and rodent pests. These pesticides get mixed with water and decrease the dissolve dioxygen level. Farmers use various types of agrochemicals that also cause pollution in soil and also in water. In due course the water bodies get high concentration of fertilizers (phosphate and nitrate rich) and consumption of this nitrate rich water by human cause various health issues especially for small children. Pesticides enter in human body through drinking water and food chain (biomagnification). Consumption of aquatic fauna with biologically magnified pesticides can cause various diseases. Some of the chemicals are very toxic and when taken by human body their side effects occur after long time and cause hormonal imbalance and may even lead to cancer.

2.1.5. Industrial Waste

Industrial waste water is the aqueous discard that contains a number of chemical substances dissolved or suspended, typically during the use of water in an industrial manufacturing process or the cleaning activities that take place along with that process. Industries are main reason for water pollution. Some industries are located around rivers, fresh water streams. These release their toxic material in river (like heavy metals Chromium, arsenic, lead, mercury etc.) (Singh et al., 2020).River Ganga is mainly polluted by industrial wastes. Factories manufacturing plastic, caustic soda and some fungicides, pesticides release their wastes directly into the river and pollute whole water. Most of the water pollutants are very harmful for crops because these pollutants are non-biodegradable, damage the growth of crops and polluted water is unsafe for drinking purposes (Singh and Gupta, 2016). The high concentration of mercury in water and in fish tissues results from formation of soluble monomethyl mercury ion, (CH_3Hg^+) and volatile dimethylmercury ($(CH_3)_2Hg$) by anaerobic bacteria in sediments.

2.1.6. Nutrients Enhancement

Nutrient is mainly a type of nourishment which is responsible for the growth of organisms. The main nutrients which cause water pollution are: phosphorous and nitrogen. These nutrients are responsible for algal growth. There are two main sources for water pollution natural and anthropogenic sources. These sources include: agricultural pesticides (nitrates and phosphates are important components of the fertilizers), sewages that can carry nutrients to streams and water, rain falling in urban areas picks up nutrients from lawn fertilizer, pet waste and also from detergents (soaps), burning fossil fuels release nitrogen oxide and ammonia into the air and then deposited into the water. So, all these nutrients contaminate the water bodies (Singh and Gupta, 2016).

2.1.7. Oil Spillage

The release of a liquid petroleum hydrocarbon mainly into the marine ecosystem, due to human activity is known as oil spill. Oil spill is a form of pollution. Due to oil discharge into the sea surface from tankers carrying petrol, diesel and their derivatives pollute sea water is termed as marine oil spill. The oil over the water surface forms a thin layer of water-in-oil-emulsion (Singh and Gupta, 2016). This water is very harmful for human use and also for aquatic flora and fauna.

2.1.8. The Disruption of Sediments

Sediment is the loose clay, sand, rocks, silt and other soil particles which settle at the bottom of a water body. Sediment (silt) comes from soil erosion and can be carried into water bodies by surface runoff to pollute whole water. The Environmental Protection Agency lists sediment as the most common pollutant in rivers, stream, lakes and reservoirs (Singh and Gupta, 2016). The soil particles, silt, sand is main cause for sediments. The sediments may damage the water body because it introduces a large amount of nutrients in the water which causes physical, chemical and biological changes.

2.2. Types of Water Pollutants

There are various types of pollutants which affect the water body. These can be broadly classified as follows.

1. Organic Pollutants
2. Inorganic Pollutants
3. Radioactive Pollutants
4. Pathogens
5. Nutrients and Agricultural pollutants
6. Thermal pollutants

2.2.1. Organic Pollutants

Organic Pollutants which are harmful for water mainly comprise of phenol, chlorinated phenols, endocrine disrupting chemicals, residual dyes present in the effluents of paper and pulp industries,pharmaceutical industries,cosmetic,textile industries, dye industries, leather, rubber and printing industries(Ali et al, 2019), polyaromatic hydrocarbons, polychlorinated biphenyls, pesticides etc.These pollutants consist of carbon, hydrogen, oxygen, nitrogen and sulphur. Organic pollutants, emitted from industry, sewage, and urban waste water, go in river, seas and pollute water and render it unfit for drinking (Singh et al., 2020).

2.2.2. Inorganic Pollutants

Inorganic pollutants which affect the water body are usually heavy metals such as cadmium (Cd), chromium (Cr), arsenic (As), lead (Pd), mercury (Hg), etc. Some chemicals such as nitrite and ammonium nitrate also contaminate the drinking water. The high level of inorganic pollutants of nitrogen (nitrate, nitrite, ammonia) and phosphate drained in river cause various health issue if find a way into drinking water. High level of nitrate and phosphate cause algal growth in our river, lakes and estuaries. Consumption of water with high concentration of nitrate affects transport of oxygen and it can cause methemoglobinemia (blue body syndrome). Due to methaemoglobin, colour of skin turn bluish colour and result serious illness to death. (Singh, et al., 2020).

2.2.3. Radioactive Pollutants

Radioactive pollutants which affect the water body include radioactive material which comes from earth crust and finds a way into water and cause pollution. Other radioactive pollutants which contaminate the drinking water are radionuclides such as uranium, thorium, and actinium and also naturally occurring radioactive elements radium, uranium etc. The artificial radioactive nuclides synthesized in nuclear power plants and nuclear weapon can also contaminate water and cause biological damage. Radium and uranium cause cancer in bones and have side effect in kidney.

2.2.4.Pathogens

Viruses, bacteria, fungi, protozoa and worms are the common pathogens which usually contaminate water and cause various diseases in human. The Pathogens enter into water body through sewage discharge. The Bacteria such as *Salmonella, Neisseria, Brucella,* *Mycobacterium, Nocardia, Listeria, Francisella, Legionella* and *Yersinia pestis* are responsible for majority of the water borne diseases. Usually, these microorganisms occur in water and if humans get infected after drinking this water(Kabral 2010).

2.2.5.Nutrients and Agricultural pollutants

Nutrient pollutants are many released into fresh water, coastal water along with urban waste, agricultural waste materials, tanks, runoff and fossil fuel combustion. Some fertilizers contain heavy metals such as cadmium and chromium and cause various environmental problems and this fertilizer mix with water cause various disease. Various fertilizer industriescontain excess of heavy metals like Hg, Cd, As, Pd, Cu, Ni and Cu. these metals deposited in soil and contaminate the water. Nutrients, primarily nitrogen and phosphorus present in chemical and organic fertilizers, normally found in water as nitrate, ammonia or phosphate. Some pesticides like insecticides, herbicides, fungicides and bactericides are rich with chemicals and pollute water (Sagasta et al., 2017).

2.2.6. Thermal Pollutants

The rise in temperature of aquatic system of 10^0C causes serious problems on aquatic life.The main cause of thermal pollution is the forest fire, and cutting of trees. The Main sources of thermal waterpollution are nuclear power plants, electric power plants, petroleum refineries, steel melting factories, coal fire power plant, boiler from industries as these all-release large amount of heat to the water bodies that leads to physical, chemical and biological changes in the water bodies. Due to high temperature, oxygen level of water decreases, and disturbs the reproductive cycle, respiratory and digestive rates among the aquatic animals(Singh and Gupta, 2016).

3. Methods of Removal Water Pollutants

Water pollution is serious problem for human and also for aquatic life.A numbers of diverse methods are applied for the removal of pollutants from water. These are described below:

- Chemical Methods
  1. Distillation Method
  2. Coagulation
  3. Flocculation
  4. Flotation and Filtration
  5. Precipitation
  6. Ion exchange method
- Physical Methods
  1. Membrane-Filtration processes (nanofiltration, reverse osmosis,electrodialysis.)
  2. Adsorption technique
- Biological treatments
  1. Biodegradation methods such as Fungal decolorization

3.1. Distillation Method

Distillation is a water purification method that utilizes heat to collect pure water in the form of vapor. This method is very effective because in this method it is clear that water has a lower boiling point than other contaminates and disease-causing elements found in water. In this method, firstly water is subjected to a heat source until it attains its boiling point, and then left it to vaporize. Then this vapour is released into a condenser to cool. Upon Cooling, vapour is reversed into liquid water that is clean and safe for drinking. Other substances that have higher boiling point are left as sediments in the container.

By this method removal of bacteria, germs, salts, and other heavy metals such as lead, mercury, arsenic, chromium etc. occur. This method has both advantage and also disadvantages. We will discuss about its advantages and disadvantages latter.

3.2. Coagulation and Flocculation

It is one of the conventional methods of water purification. In this method, chemicals are used for the removal of particles suspended in water. Various types of particles removed by this method include inorganic particles clay and silt and some algae, bacteria, viruses, protozoa and some natural organic matter. Some inorganic coagulants such as aluminiumsulphate (or alum) or Fe^{3+} salts or iron chloride show affinity towards these particles. So that the negative charges on the particles are neutralized by inorganic coagulants and get precipitated. (Bernard et al., 2019)) In this process, small particles are combined to form large aggregates (flocs) and dissolved organic matter also get absorbed on to particulate aggregates so that these impurities can be removed in solid/liquid separation process.

3.3. Filtration Technique

Filtration is one of the best techniques for water purification and can be done by using multimedia filers. In this technique water is passed over a medium (filter), so that the solid dust particles are settled down on filter and the filtered water comes out. This method uses both physical and chemical processes for the purification. Filtration eliminates both large and small size contaminants, heavy metals.

Since early days filtration technique has been found most valuable because it removes all the harmful bacteria, microorganism and small dust particles on the basis of their sizes. Multilayer filtration can also be used to improve its efficiency. The cellulose based filter paper is highly used because it is affordable and shows high efficiency.

3.4. Adsorption Technique

Adsorption is a surface phenomenon in which adsorbate molecules are attracted and held at the surface by the adsorbent. As a result, the concentration of a substance increases on the surface (Gupta and Ali, 2003). Adsorption process is usually affected by temperature, nature of the adsorbate and adsorbent, and the presence of pollutants and some atmospheric conditions (pH, concentration of pollutant).Adsorption phenomenon is used for the removal of Organic as well as inorganic pollutants. Adsorbents used for the purification of water are usually of two types: natural adsorbent and synthetic adsorbent. Natural adsorbents include clay, charcoal, zeolites, ores and synthetic adsorbents are usually prepared from agricultural wastes, house hold wastes, industrial wastes, sewage and polymeric adsorbents. The natural adsorbents are usually cheap, easy to supply and have significant potential. Activated charcoal is used as adsorbent for organic pollutants. Activated charcoal granular and powdered is used for the removal of odour, colour, taste, and other organic and inorganic impurities from industrial and domestic waste water body (Rashed, 2013). Among the adsorbents, activated carbon is highly effective as adsorbent because of its high surface area of 500-1500 $m^2g^{-1}$and high pore volume of 0.3-1.0 cm^3g^{-1}.

Adsorption technique is one of the most efficient, economic and versatile techniques, mainly used for the purpose of high-quality treatment process. It removes dissolved organic pollutants, such as dyes, industrial waste material, chemicals. Adsorption results into decolourization of the wastewater. A wide range of conventional adsorbents like activated carbon, silica, alumina are used for the removal of toxic and hazardous pollutants from waste water and removal of chemicals from water. Removal of nitrogen compounds, such as nitrates, ammonia through adsorption by local clay has been reported in the literature (Battaset al., 2019).

3.5. Ion-Exchange Method

Ion-exchange is most rapid and reversible process used for the removal of impurities which is present in the water using ion-exchange resins. The ion-exchange resins are basically of two types- cation-exchange and anion-exchange resins. Cation exchange resins contain negative charged ions and it attract positively charged ion present as impurity and anion exchange resins contain positively charged ions that it attract negative charge ions of impurity material in water.

The ion-exchange process widely used in water treatment industry; sea water and brackish water desalination, water softening, removal of heavy metals, harmful ions and dissolved organic contamination. (Ahmad et al., 2019)

Here is the list of main ions present in natural or polluted water:

Cations	**Anions**
Magnesium (Mg^{2+})	Nitrate (NO_3^-) Carbonate (CO_3^{2-})
Calcium (Ca^{2+})	Chloride (Cl^-) Bicarbonate (HCO_3^-)
Sodium (Na^+)	Sulphate (SO_4^{2-})
Potassium (K^+)	Carbondioxide (CO_2)
Hydrogen (H^+	Silica (SiO_2)
Hydroxide (OH^-)	

In ion exchange process water passes through bead-like spherical resin material, so that ions in the water are exchanged with other ions in the beads. Softening and deionization methods are also used for water purification. Softening method is used primarily to reduce hardness of water. In softening method, beads exchange two sodium ions for every calcium and magnesium ion and these ions removed from the water and water become soft.

Deionization beads remove both cation and anion from water; they contain hydrogen ion for the removal of anion and contain hydroxyl ions for the removal of cation. The cation exchange resins, made of styrene and divinylbenzene containing sulfonic acid groups, and it exchange hydrogen ion for any cations (Na^+, Ca^{2+}, Al^{3+}.Also, anion exchange resins, are made from styrene containing quaternary ammonium groups. These exchange a hydroxyl ion for any anions (Cl^-).So that hydrogen ion from the cation exchangers combines with the hydroxyl ions from the anion exchanger and made pure water.

Here is the pictorial representation of water softening using resins.

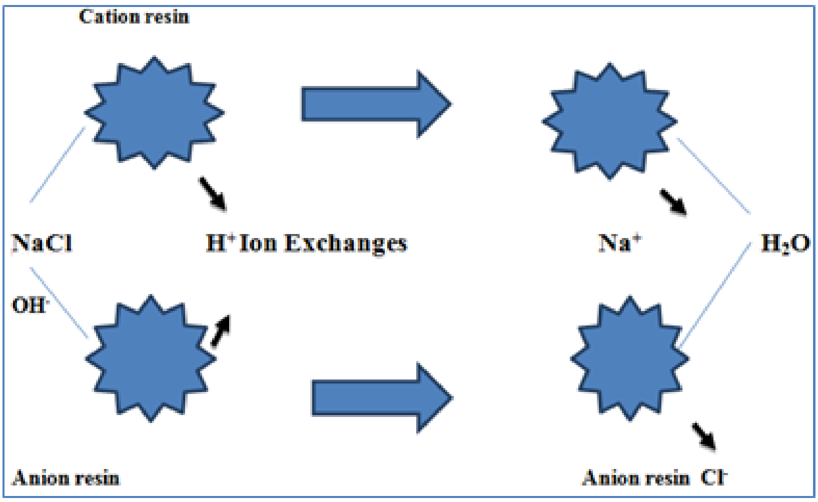

Figure 1. Working of anion and cation exchanging resins.

3.6. Membrane Filtration

Membrane filtration is very efficient and economical way. Membrane is a thin polymeric solid which is semipermeable in nature, and it can restrict the passage of certain chemicals. Membrane filtration technique is used for the removal of bacteria, microorganisms, particulates and natural organic material, which impart color, tastes and odors. There are different types of membrane filters available on the market.

Water purification using membrane filtration can further be divided into three categories namely; microfiltration, nanofiltration and reverse osmosis.

3.6.1. Microfiltration

It is usually a membrane separation process, using the membrane with a pore size of 0.03 to 10 microns (1 micron= 0.0001 millimeter). It is physical method of separation to removal of suspended solids and bacteria from water through membrane. Microfiltration does not remove dissolved contaminates. It is a pressure driven process (Manimekalai, et al., 2017). Membrane microfiltration is a crucial part of a bioreactor process used in municipal wastewater treatment. Material which is removed by membrane microfiltration includes sand, silt, clays, cysts, algae, and some bacteria species. This technique is also used for the removal of synthetic organic matter.

Examples of micro filtration application are:

- Cold sterilization of beverages and pharmaceuticals
- Separation of oil/water emulsions Pre-treatment of water for nano filtration or Reverse Osmosis
- Clearing of fruit juice, wines and beer
- Separation of bacteria from water (biological wastewater treatment)
- Microfiltration membrane can be used for versatile fields for separation of virus, aerosols and immiscible macromolecules from fluids (Pal, 2020).

3.6.2. Ultrafiltration

Ultrafiltration technique is widely used for water purification. Ultrafilters have pore size of approximately 0.002 to 0.1 micron and operating pressure of 200 to 700 kPa. Ultrafiltration membrane usually made of both organic and inorganic material and various polymers also used for the manufacture of UF membrane. (Wenten, 2002) The polymeric materials such aspolysulfone, polyvinylidene fluoride, polyacrylonitrile, polyimide, aliphatic polyamide is used for preparation of ultrafilters because of their specific properties such as molecular weight, chain flexibility, chain interaction etc. Ultrafiltration technique is used for the removal of microorganism species as well as some viruses and harmful material.

Ultrafiltration is a water purification process in which water is passes through a semipermeable membrane. Suspended solids and high molecular weight solutes remain one side of the membrane, and water and low molecular weight solutes filter through the membrane. So that water is purified.

3.6.3. Nanofiltration

Nanofilters have a pore size of approximately 0.001 microns. Nanofiltration remove smallest moiety in the water and purify it. It is widely used for the removal of cysts, bacteria, viruses and many small particles of dust in water. Nanofiltration technique falls between ultrafiltration and reverse osmosis. This technique used mainly for the wastewater treatment and industrial applications for the removal of ions and organic substances (Adapted, 2005).

3.6.4. Reverse Osmosis

This technique is most effective for the removal of all inorganic contaminates from water and also for radium, natural organic substances, pesticides, cysts, bacteria, viruses, contaminate ions and dissolved non-ions. It operates immediately and requires low effluent concentration.

4. ADVANTAGESAND DISADVANTAGES OF VARIOUS METHODS USED IN WATER PURIFICATION

The methods which have described in the forgoing pages for the treatment of water have to various heir pros and cons. Each method has its own constraints in terms of cost feasibility, efficiency and formation of some toxic by-product. These have been listed in the following table:

Table 1. Comparison of various methods of water purification

Process	Advantage	Disadvantage
1. Distillation	1.Removes a broad range of contaminants 2.Reusable	1.Some contaminants can be carried into the condensate 2.Requires careful maintenance to ensure purity 3. Consume large amount of energy
2.Ion exchange	1.Removes dissolved inorganic and organic ions 2. Can be regenerated 3. Low costly	1.Does not remove completely bacteria, particles 2.High operating cost over long term
3.Filtration	1.It is very easy to use 2. cost effective 3. The odor and taste of water will change 4.harmful toxins can be removed from hard water	1.It does not remove all contaminates and germs from filtered water. 2.Cleaning and care of equipment is must required otherwise it does not work properly.
4.Membrane filtration 1.Microfiltration 2.Ultrafiltration 3.Nanofiltration 4.Reverse Osmosis	1. Small space required 2.Simple, rapid and efficient 3. No chemical required 4. Eliminates all types of dyes, salts and minerals derivatives 5. Eliminate microorganisms (MF, UF, NF, RO), volatile and nonvolatile organics (NF, RO), dissolved inorganic material and phenols, Cyanide.	1.High investment costs for small and medium industries 2. High energy required 3. High maintenance and operation process 4. Limited flow rates 5.The choice of the membrane is differing according to hardness, reduction. 6. In low solute feed concentration it is not much more effective.

5. NANOTECHNOLOGY BASED REMOVAL OF POLLUTANTS FROM WATER

5.1. Nanocellulose Based Water Purification

Nanocellulose is present naturally and can be manufactured by renewable resources. Nanocellulose comprises of nanocellulose fibers (CNFs), nanocellulose crystal (CNCs) and bacterial nanocellulose (BNC). Nanocellulose is used preferably for the water treatment processes (Gopakumar et al., 2019*)*. It is mainly used for the removal of heavy metal ion, dyes, oils etc. from contaminated water.

Nanocellulose works as an adsorbent due to its high specific surface area, presence of enormous hydroxyl group, high degree of crystallinity and numbers of active sites. Nanocellulosic crystals and fibers have been used as bioadsorbents for the removal of silver, cadmium, nickel and lead ions from polluted water (Liu et al., 2014; Kardamet al., 2014).Nanocellulosic materials are also used in removal of organic pollutant and dyes from waste water. Organic dyes generated by various industrials sources adversely affect the environment and human beings. Organic dyes can display cationic, ionic and non-ionic properties and having complex aromatic structure. These dyes can be removed from waste water by the use of carboxylated cellulose. Carboxylated CNCs prepared by TEMPO-Mediated oxidation method containing high amount of COOH nearly 2.1 mmol/g, results in higher uptake of cationic dye (769 mg/g) methylene blue in comparison to CNCs having sulphate group (118mg/g) at same pH value (9) (Batzmen et al.,2014). Literature is available on the removal of dyes from waste water by nanoporous membrane having cellulosic nanocrystals (Karimet al., 2014). Organic dyes mixture (methylene blue with Rhodamine B or methyl orange or crystal violet) are selectively adsorbed and separated by means of cellulose nanocrystals (CNCs)(Carpenteret al., 2015). The dye CNC surface functional group interaction was evaluated by pristine and surface functionalized CNCs, polydopamine (PD) and melamine-formaldehyde coated CNCs. The adsorption studies on methylene blue and methylene orange dye mixture results greater adsorption for methylene blue with adsorption efficiency of 85.78% while in PD-CNC interaction 100% efficiency is observed. Yu et al.,(2013)used carboxylated cellulose nanocrystal for adsorption of heavy metal(Pb^{2+} and Cd^{2+}) from their aqueous solution.

However, nanocellulose is also used in flocculation method in which the components which are present in waste water are removed by combination of colloidal particles due to electrostatic interaction. An adsorbent prepared with carboxylate functionalisation in which maleic anhydride is joined on primary –OH of CNC. So that it forms a bidentate relation between dye and adsorbents carboxyl group. It is used to isolate cationic dyes from waste water (Qiao et al., 2015). Zhu et al.,(2011),have used spherical Fe_3O_4/bacterial cellulose nanocomposite for adsorption of heavy metal ion by a phenomenon named agitation fermentation. Spherical Fe_3O_4/bacterial cellulose nanocomposite was biosynthesized from *Gluconacetobacterxylinum* using pH controlling embedded method. The result shows that Pb^{2+},Mn^{2+},Cr^{2+} are adsorbed and eluted out by this method.

Nanocellulose is used as an adsorbent because it is economic, renewable, and have abundant resources. Nanocellulosic hydrogels have been prepared from long nanofibrils of 3-15 nm diameter cleaved from wood pulp. To form highly porous nanocellulose aerogels, hydrogels were dried by using vacuum-drying, freeze-drying or supercritical CO_2 drying. These cellulose nanofibers of aerogels have oleophilic coating of titanium dioxide, capable of oil absorbance thus used for removal of oils floating on water (Korhoneet al.,2011).

Zhanget al.,(2014) shows selective removal of oil from waste water by silylatednanocellulose sponge which is ultra lightweight and flexible. Yang et al.,(2014) shows adsorption of chromium(VI) and lead(II) by thiol modified cellulose nanofibers composite membrane. To increase the adsorption capacity of lead and chromium, cysteine is grafted with oxidised cellulose nanofibers which are embedded in electrospunpolyacrylonitrilenanofibers. In taking consideration of pH and contact timing, the adsorption data of CNF nanofiber composite membrane of Cr (VI) and Pb(II) Shows high adsorption capacity of nanofiber membrane for both Cr(VI) (87.5mg/g) and Pb(II) (137.7mg/g). Zhou et al., (2014) have prepared carboxylated cellulose nanofibrils-filled magnetic chitosan hydrogel beads which have been used as adsorbents for removal of Pb(II). For specific absorption and separation of organic liquid ultra-light nanocomposite aerogels of bacterial cellulose and reduced graphene oxide was used by Wanget al., (2014). In this method freeze-drying process was used and high absorption of organic solvent took place due to reduction of graphene oxide using H_2 gas. Absorption of 135–150 g of organic liquids per gram of their own weight resulted even with a high content of 80% Bacterial cellulose in the nanocomposite aerogel. By using carbon nanotubes membrane, Leeet al.,(2015)developed a millimeter thick ultrafiltration membrane which resulted permeability of 30000 $L^{-1}m^{-1}$ h^{1} $bar^{-1}$from 2400 $L^{-1}m^{-2}$ h^{-1} bar^{-1}.

5.2. Graphene Coated Nanofilters

Graphene coated nanofilters are more advanced form of separation membrane and they are used in water desalination, proton conduction, and energy storage. Most common method for preparing graphene-based filtration membrane is vaccum filtration method. In this method film forming material is uniformly dispersed in solvent and then this material is accumulated on the substrate under vaccum filtration because of fluxion function of solvent molecule (Salvetatet al., 1999). Nanofiber nets are used to filter graphene oxide solution after which the membrane is dried (Salvetatet al., 1999).Wanget al., prepared graphene oxide membrane by using vaccum filtration method. Other methods which are used for the formation of graphene oxide membrane are Layer-by-layer self-assembly method in which driving force for the membrane formation is electrostatic interaction between ions which helps in maintaining stability between the membrane layer. Other methods which are used for preparation are spin coating, spraying method, dip coating etc (Salvetat et al., 1999).

As of now, microorganisms and bacteria are major water pollutants. Sunet al., (2015) has fabricated the graphene-oxide silver nanoparticles (GO-AgNPs). These nanoparticles are composite into cellulose acetate (CA) membrane. These have been found better than the CA membrane. The result of contact angle shows that on modifying modified GO-AgNPs, the hydrophilicity of membrane increases, when they are tested on continuous filtration, only 46% relative flux drop was measured which is less than CA membrane having reflux drop of 88% when filtration continuously done for 24 hrs. High antimicrobial activity has been reported by presence of GO-AgNPs composite membrane which results 86% inactivity of *E.coli* bacteria when in contact with membrane for at least 24 hrs.

Hanet al.,(2013) fabricated ultrathin graphenenanofilter membrane (uGNM) on microporous substrate by using chemically converted graphene (CCG) for the purpose of water purification. Well packed layer structure of ultrathin graphenenanofilter membrane was observed which was formed by CCG sheet. The efficiency studies conducted for the purpose water purification techniques using dead end filtration device showed thatuGNM had high pure water flux(21.8 L $m^{-2}h^{-1}bar^{-1}$) as well as high retention(>99%) in case of organic dyes and moderate retention (20-60%) for ion salts. Thus, uGNM shows great application in the field of water purification due to high performance, low cost, and simple solution based fabrication process.

Researchers have used photocatalytic ultrafiltration water treatment under visible light by partially reduced graphene oxide/TiO_2 (Athanasekou et al., 2014). The hybrid process named as photocatalytic/ultrafiltration process involves the integration of partially reduced graphene oxide/TiO_2 composite membrane with water a filtration device which makes combination of membrane filtration with semiconductor photocatalysis. By using dip-coating technique, the TiO_2 nanoparticles with graphene oxide sheet stabilized the pores of ultrafiltration channels in dark UV and visible light. Santhoshet al.,(2014) prepared Graphene-Fe_3O_4 composite by solvothermal method from graphene oxide and $FeCl_3.6H_2O$. The presence of Fe_3O_4 sphere with size range of 200nm to 250nm, attached with graphene layers had high density. These composites have high adsorption capacity and high adsorption rate towards removal of Pb ions and organic dyes from waste water.

5.3. Electrochemical Carbon Nanotube Filtration

During recent years the electrochemical active carbon nanotube filter is used widely for waste water treatment (Jameet al., 2016).These filters are used for the removal of biological and chemical contaminants form water due to properties like high stability, great flexibility, and large surface area. Hundred of individual tubes are intertwisted with each other by vander Waal force of attraction to form CNT filters. And due to this the surface area becomes relatively high (30-500 m^2 g^{-1}). These are used to absorb biological and chemical contaminants from water. The pollutants present in water can be destroyed either by direct oxidation or indirect oxidation in electrochemical processes. Anodic electron transfer reaction is used in direct oxidation process in which compounds are first absorbed on anode surface and then by virtue of anodic electron transfer these are destroyed (Brittoet al.,2012) while strong oxidants are used in indirect oxidation process. CNTs have been observed to strongly adsorb ionic dyes and chlorophenols.

Ti/PbO_2 electrodes are manufactured by electrodeposition method with PbO_2 coated on Ti. These electrodes are used for the electrochemical oxidation of phenol.If we consider current density, initial phenol concentration, initial solution, pH, different temperature and Fe^{2+} dose on Ti/$PbO_2$for electro chemical degradation at 50^0c.and at pHvalue 2 which have a potential difference of 5V. The complete removal of phenol takes place (Saratale et al., 2016). It is also shown that removal rate of phenol is directly proportional to current density i.e., if current density increase removal rate of phenol is also increased. Other method of is also reported. Stucki et al., (1991), used Ti/SnO_2 as anodic material for the removal of phenol from waste water. Also, the use of SnO_2-Sb_2O_4-CNT anode showed 90% removal of phenol (Huet al., 2010*)*.

The removal of organic contaminants from waste water by electrochemical advanced oxidation processes (EAOPs) has been widely accepted (Garciaet al., 2015). For the treatment of secondary effluent from sewage treatment plant Anodic oxidation with a boron-doped diamond (BDD) anodes have been used. In a study, the sewage treatment plant containing 29 target pharmaceuticals and pesticides was treated with electrochemical advanced oxidation processes (EAOPs). The study of effectiveness of the method was done on the basis of various parameters such as; contaminants decay, dissolved organic carbon and chemical oxygen demand removal, current applied and pH effect. The results were highly encouraging as outflow organic matter and detected contaminants were completely mineralized and can also be obtained by this EAOP because on BDD surfacehydroxyl radical are formed. At BDD anode the active chlorine species (Cl_2/HClO/ClO^-),are formed due tooxidation of Cl^-ions present in the wastewater, which are acts as oxidizing agents to obtain chloramines and organohalogen as a by-products and the production of $ClO_3^-$and ClO_4^-take place due to anodic oxidation of HClO/ClO^-species.

Chromium (Cr) is a major pollutant present in fresh water because dyes and paints, chrome plating, and leather tanning are manufactured by using chromium (Barnhart 1997). Chromium acts as contaminant when it is present in hexavalent state .Wanget al.,(2014) performed an experiment to removechromium using potentiostat. The experiment was performed in the batch mode.CNT or SSM electrode was used as cathode, a piece of carbon paper as an anode and Ag/AgCl was used as a reference electrode. The carbon paper was used to prevent the oxidation of Cr (III) to Cr (VI) (El-Sharif et al., (1999);El-Sayed et al.,(2009).

Various metallic pollutants such as copper and nickel have also been removed from waterby constructing an electrochemical cellin which conductive carbon fiber cloth act as cathode while platinum coated titanium panel as anode at pH value 6.8 and having low voltage supply energy of 10 V.(Tran et al.,2017, Bankole et al., 2019, Fugetsu et al.,2004).

Two different kind of nano-adsorbent namely purified carbon nanotubes (P-CNTs) andpolyhydroxylbutyrate functionalized carbon nanotubes (PHB-CNTs), are used to remove heavy metals from industrial waste water by batch adsorption. These 2 types of nano-adsorbents are prepared by catalytic chemical vapour deposition (CCVD) method. Various factors should be taken in consideration like effect of contact time, dosage, temperature, and pH. On the basis of ion exchange and electrostatic forces mechanisms, it has been proven that nano-adsorbent have great ability of removal of heavy metals (As, Pb, Cr, Cd, Ni, Cu, Fe, and Zn) from industrial waste water (Bankole et al., 2019).

Literature reveals that a number of attempts have been successful where CNTs and modified CNTs have been used for water purification. Vecitiset al.,(2011) has removed methyl orange dye from waste water by using CNT as an anode having efficiency of 98%.Liuet al.,(2014)has successfully removed oxalate with the help of Graphene-CNT acting as anode and Ti as cathode. Liuet al., (2014) used coated CNT filters with TiO_2 and used this for removal of arsenic via simple filtration-steam hydrolysis method. Methyl orange was also removed by this process with efficiency of 96% when CNT act as anode as well as cathode (Jame and Zhou 2016, Yang et al., 2004). removed fulvic acid from waste water by using electrochemical CNT in which woven(active carbon fibre) ACF+Fe act as anode and woven ACF act as cathode (Yanget al., 2004).

6. Merits of Nanotechnology

In comparison to conventional methods, the nanofilters have greater advantages like these need less pressure to pass water through filters, have large surface area, have higher efficient, and can be easilycleaned by back flushing method.

Nanoadsorbents also have great advantages like they have high specific surface area for adsorption and have high adsorption rate which can be implicated for removal of various contaminants like heavy metal, organic materials and bacteria from waste water.

While nanometal and nanometal oxide (e.g., nanotitanium dioxide, magnetic particles etc.) have properties like supramagnetic facilities separation (separations of components from a mixture using magnets), photocatalytic properties, abrasion resistance (resistance to surface wear) and are low cost method. These are also useful for the removal of heavy metals, radionuclides, media filters, powder and pellets from contaminated water. The membrane processes like nanofiltration, nanocomposite, self-assembly, aquaporin based and nanofiber membrane have properties like they provide a physical barrier for a substanceon the basis of pore size and molecular size and these channels are automated and reliable for purification of water. The major benefit of using such type of nanoparticles is that they can be used for any type of waste water treatment.

Oil from waste water can be removed by various methods in which use of organic sorbent is generally imposed but the absorption capacity of organic absorbents is limited and their incorporation with inorganic sorbents become expensive to use in wide areas for removal of pollutants from waste water. Also, these materials are not biodegradable. In comparison to the nanofibers and nanocellulosic materials which have properties like biodegradability, renewability, low density, low cost and environment friendly characteristics are better options for the oil absorbance from waste water.

Membrane separation techniques are preferred over other traditional and conventional methods of water treatment, such as disinfection, distillation, or media filtration because, in membrane separation methods there is no need of chemical additives, thermal inputs, or requirement ofregeneration of media which is used (Yanget al.,2014).Maxwell called these techniquesas 'sorting demon' commercial separation.These membranes separate selectively and reliably with high efficiency (Zhouet al., 2014;Wanget al., 2014).While in past few decades, the use of gas separation, evaporation and electrochemical membrane processes for environmental separations has increased gradually, still the largely used techniques for water treatment application are pressure-driven membrane processes (Wanget al., 2014;Pendergast and Hoek 2011).

The conventional membrane materials have less lifetime than carbon nanotube-based membrane because the latter has excellent mechanical properties (Pendergast and Hoek 2011;Mulder 1996).In comparison to conventional method electrochemical oxidation of organic contaminates take less time for treatment of waste water(Jame and Zhou 2016).Wastewater treated by electrochemical oxidation method is widely used because it removes organic and biological contaminants safely and effectively (Chenet al.,2008). These techniques have some advantage like contaminants removal frequency is high and organic compounds are completely broken into CO_2 and H_2O like small molecules (Sunet al., 2014; Bayram and Ayranci 2010).

7. FUTURE PERSPECTIVE

The use of nanotechnology for the treatment of water is investigated widely but further research is needed in the area to improve thequality of the nanomaterials and to find the low-cost materials. There is an urgent need for a better technique by which the nanoparticles can attach on the surface of reactor or filtration layer so that the separation take place efficiently and decreases the overall cost of separation process. Particularly surface coating technique should be developed further by using nanomaterial suspension to minimize the membranes fouling. Research on novel immobilization and magnetic separation is needed.Research shows that nanomaterials can act as a very promising sorbents which can remove pollutant from water as lead, cadmium and copper is removed by multiwalled carbon nanotubes in comparison to commonly used sorbent activated carbon. Extensive research is needed to develop more nanoadsorbents.

In future smart membrane can be prepared which can detect and remove pollutants simultaneously or only a single membrane can be used to perform multiple tasks like the detection, separation and purification commutatively.The research is going on the membrane having microbial activities and whose membrane efficiency can be regulated automatically by using a sensor that is attached on the membrane.

Some nanomaterials show hazardous effect on environment as well as human beings. Maet al., (2013) showed phytotoxicity of nanoscale zero valent iron (nZVI) on two plants species while Chenet al.,(2016) reported toxic behavior of zinc oxide nanoparticles to lemna minor which was caused by dissolved zinc.Liet al.,(2015) showed toxic effect of nano TiO_2 on algae, so toxic behavior of nanomaterials should be studied further and removed in future to make them safer for use. The toxic behavior of nanomaterials and development of non-toxic materials is a field that has vast opportunities for the research. Besides, the cost cutting of such materials is also a research topic. Comparative performance of nanomaterials shouldalso be studied in future for better understanding of their working and development of suitable nanomaterials can be further used for water treatment (Luet al., 2016; Nnajiet al., 2018).

Development of composites having multi-metallic nature is a great area of research for wastewater treatment. Because these composites have various properties like photocatalytic, antimicrobial and can act as sensing adsorbents. In future, the work on the nanomaterials derived from nature such as cellulose containing nanomaterials is most promising due to their environment friendly and non-toxic nature. It is also great area of research to formulate new technologies of synthesis and processing which require no hazardous chemicals and development of environment friendly nanofiber membrane is also a greater field research in the field of removal of water pollution.

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Chapter 18

ROAD MAP TOWARDS FUTURE PLANNING FOR WASTE MANAGEMENT IN CIRCULAR CITIES: DECISION MAKING STRATEGIES AND COMPLEMENTARY TOOLS

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ABSTRACT

Increasing population and urbanization are leading to increase in industrial activities and they all have direct correlation with waste generation. Traditional waste management applications, which are landfilling and incineration, have become inefficient due to increase in waste amount, their adverse environmental impacts and resource depletion. Nowadays, new understandings about limited natural sources and global environmental problems such as climate change lead to shifts in waste management strategies. Policy makers brought the concept of Circular Economy (CE) in front and take significant actions to promote waste management in the direction of reduction, reuse, recycling, recovery, and usage of environmentally friendly materials. The fundamental principle of CE is to prevent the loss of materials and natural sources by closing the loop in production and waste management activities and minimize the disposal of sources as waste. Since waste management is usually applied at municipality level, implementation of CE principles is expected to be at city level and new cities which are shifted from linear economy to CE are called as Circular City. Transition from linear cities to circular cities requires significant changes and revisions in various areas including the prediction of waste amount and type for planning, re-design of infrastructure for waste separation & collection, developing new policies for waste management strategies, designing and operation of new material recovery facilities. Therefore, circular cities need developing roadmaps towards future planning for waste management. Usage of various decision-

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making methodologies and complementary tools is urgent hence, developing roadmap for new waste management strategies is complicated because of the presence of several factors influencing the decision. For this purpose, waste management studies have been using decision making methodologies and complementary tools intensely since a few years when international organizations are clearly announced action plans for the transition to circular cities. This chapter aims to review the waste management studies that have been published lately and contribute to development of roadmaps for the transition to circular cities. To be more conclusive, reviewed studies are limited to include the most commonly used decision-making methodologies and complementary tools. In this context, the studies using Multi-Criteria Decision Analysis (MCDA) methods and the complementary tools including Material Flow Analysis (MFA), System-Dynamic Based Approach (SD), Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) are selected. The studies reviewed in this chapter demonstrated that these tools have potential to contribute to roadmap planning of waste management strategies for circular cities.

1. INTRODUCTION

Waste is the material or product that is not functional anymore for its primary purpose and is usually sourced from industrial or human activities (Sharma and Jain 2020). Production amount, composition, rate changes of the waste varies at local scale with respect to culture, habits, industrial differentiations, local economy etc. (Thokozani 2015). Increase in waste is directly proportional with population growth, industrial activities and increase in urbanization (Luo et al. 2021). In 2013, total global solid waste amount was around 17 billion tons and projected value for 2050 is about 27 billion tons (Laurent et al. 2014). Most common waste composition in municipal solid waste includes organic (food) wastes, plastics, metals, glasses and composition of industry sourced waste depends on raw materials and process (Laurent et al. 2014). According to 2018 data of World Bank Group (as cited in Sharma and Jain 2020), types of waste handling methodologies are as follows: 36.7% landfilling, 33% open dumping, 11% incineration, 13.5% recycling, 5.5% composting and 0.3% other. Before 21st century, waste management included only landfilling and incineration; however, this concept is converted to Integrated Waste Management (IWM) which is based on a hierarchy including reduction at source, reuse, recycle, recovery, landfilling, respectively. Several factors like lifestyle, urbanization, industrial activities, increasing in consumption and waste generation resulted in transition to IWM.

Transition to IWM gain strength with the announcement of United Nations (UN) Sustainable Development Goals (SDGs). Significance of the sustainable management was discussed in many conferences around the world and calls for the regional actions are announced (Maina, Kachrimanidou, and Koutinas 2017). The most important result of SDGs is the entrance of "Circular Economy (CE)" concept to the production-waste generation cycle. CE understanding provides a waste management perspective which mainly based on reduce, reuse, recycle and recover as it was mentioned before. The aim of CE is to close the loop between raw material/energy usage and waste generation in order to increase resource efficiency. So, waste gain value as a secondary product with reuse/recycle/recovery technologies. In 2018, CE Package (CEP) is accepted by the European Commission (EC). Production, consumption, waste management and the secondary raw materials market are included as a cycle in CEP and necessary measures are provided with an action plan (Venâncio and Pope 2018). CEP aims to keep the materials in production-consumption cycle for as long as possible in order not to lose them in terms of economy and environment. The European Union (EU) member states are responsible to adapt directives included in the CEP to their national legislations. Moreover, landfilling is allowed up to 10% after 2035 by EU legislations. Average recycling ratio of 28-EU Member States is only 46.4% of municipal solid waste (Kůdelaa et al. 2020). This shows that the transition to CE requires huge effort in the following 15 years. Zorpas 2020 stated that there are concerns for transition to circular city when the targets of Green Deal strategy by EU and UN SDGs are considered.

Waste management is usually handled at local scale, city level. Since CE is closely related with waste management, transition to CE is expected to be planned at city level. The concept of "Circular City" emerged as a result of CE transition. Cities which apply waste management with landfilling and incineration are in the category of linear economy due to the loss of materials as waste. Circular city can be defined as managing product-waste relationship to prevent/minimize occurrence of wastes with efficient management methods in cities which has a main role for producing wastes with high urbanization rates. Particularly, concept of circular cities is leading to new waste management strategies to optimize resource efficiency and waste minimization both for urbanized and industrial areas. This waste management strategy, which is based on "4R: Reduce, Reuse, Recycle, Recovery," is mentioned within the concept of CE.

Transition from being linear city to circular city is challenging due to complicated IWM strategies shown in Figure 1. Waste management strategies to reduce and reuse the waste at source, to allocate the waste streams with optimum collection and separation routes and to select the most proper recycle/recovery method and technology have to be developed in phase of transition to circular cities. Since all of these components are newly introduced with the concept of circular city and each component requires numerous detailed analysis for their applications; developing roadmaps for efficient IWM strategies for circular cities should be supported with decision making methods and complementary tools to find/decide main points quickly and efficiently. Plastic, e-waste, construction & demolition waste, bio-waste such as food waste are the significant components to be recycled/recovered within the concept of IWM.

Not only waste management components, but also socio-economical level of the countries/cities affects the challenge level of transition stage. Coban, Ertis, and Cavdaroglu 2018 highlighted the need for developing countries for fast adaption to waste management since developing countries usually have high population increase and new technology applications that leads to consistent increase in the amount and diversity of waste. Moreover, waste trading to achieve integrated regional waste management for easier adaptation to circular city transition can be considered as an alternative waste management strategy (Josimović, Marić, and Milijić 2015). Industrial and urban symbiosis planning gains importance in terms of integrated regional waste management (Yee Van Fan et al. 2021). Therefore, developing roadmaps for efficient IWM strategies for circular cities should also consider the socio-economic aspects that makes it more challenging and increase the need for decision making methods and complementary tools.

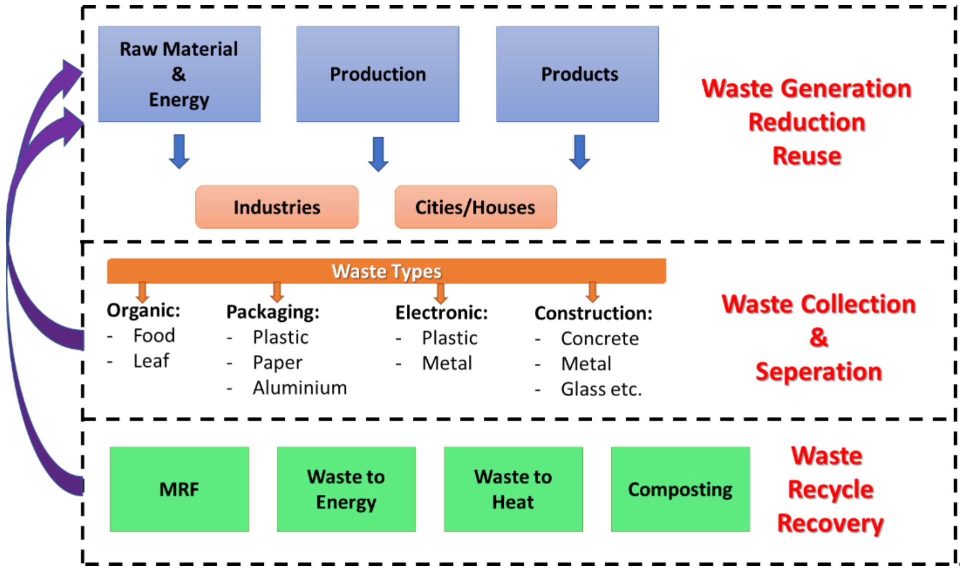

Figure 1. Integrated Waste Management components.

Mathematical models including optimization, multi-objective and multi-criteria decision models are the most frequently used decision support methods for IWM (Sing, 2019). The main topics of decision support studies include geographical scope, type of waste, technological solutions, optimal location, waste supply chains and optimization of technological processes (Vlachokostasl et al. 2021). The most frequently used complementary tools for technical, economic, environmental and social analysis are Material Flow Analysis (MFA), System Dynamic (SD), Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA). Decision support methods are combined with complementary tools in recent studies (Milutinović et al. 2017). Therefore, this chapter provides the literature review from recent studies including the decision support methods and complementary tools of MFA, SD, LCA, LCC, S-LCA which can contribute to the development of roadmaps through future plans for IWM transition to circular cities. Complementary tools are limited to selected ones in order to have a more efficient summary of most widely used tools with high potential for applicability. Plastic, e-waste, construction & demolition waste (C&D), food waste is most commonly studied waste compositions.

2. Waste Management

Waste is defined as the items that are not useful anymore for any purposes at a certain place and time. Waste management includes the waste generation, separation, collection and disposal. Therefore, waste can be a serious problem for human health and environment when it is not managed properly. Depending on the dynamics of the century in terms of technological, economic and environmental perspectives, waste management technologies have changed. In 18th Century, cholera pandemic had started because of improper management of wastes in Great Britain. In 19th Century, the first waste management activities started to prevent diseases and they were incineration and uncontrolled dumping at those years. However, environmental hazards by emissions and human health hazard by particle respiration occurred due to the incineration and illegal dumping and different management activities emerged (Sandhu 2014). In the 20th century, landfill was the most preferred waste management activity; however, there are lots of negative impacts of landfill like odor, groundwater pollution, air emissions, soil pollution etc. In addition, landfill occupies precious area in cities and there will be no place to burry at future time (Walsh 2002; Hoogmartens, Eyckmans, and Van Passel 2016; Jianguo et al. 2010).

In the early 21st century, concept of waste management shifted to 4R (Reduce, Reuse, Recycle, Recovery) principle which is a requirement of sustainable development in order to close the loops in resource consumption. As it was stated above, landfilling is the most applied waste management method (36.7%) worldwide, which is followed by open dumping (33%), recycling (13.5%), incineration (11%), composting (5.5%) and other methods (0.3%) (as cited in Sharma and Jain 2020). This distribution changes regionally depending on the chosen waste management strategy. Open dumping has a big portion in waste management types in developing and under developed countries (Venâncio and Pope 2018). Open dumping is illegal disposal of wastes and it is not a suitable method for waste management with respect to health and environmental concerns because of emissions and leachate sourcing from waste. Open dumping is frequently used in non-developed countries. Incineration method is used for mass and volume reduction, detoxification, sterilization and energy gain with burning high calorific value of wastes (Chou et al. 2009). Heterogeneous structure of municipal solid waste complicates incineration because of moisture percentage, combustible/non-combustible material ratio etc. At the end of the incineration process, ash is generated which also must be managed (Manjunatha et al. 2020). Composting is a method that organic waste stabilized with microorganisms with the absence of toxic materials and pathogens (Bernai et al. 1998). Recycling method gains importance with depletion of natural resources and decreasing landfill capacity with increasing urbanization since recycling converts waste from landfill and waste is gained back as secondary product.

Waste management is transformed to IWM after the adaptation of sustainability and CE principles all over the world. IWM expands the conventional waste management activities, which is ultimate disposal with landfilling or incineration, to 4R applications. This approach is a requirement of sustainable waste management in order to reduce environmental effects and increase the economic and social benefits by closing the resource consumption loop. Global environmental, economic and social challenges such as climate change and resource depletion lead to the application of sustainability principles in all management activities including waste management. Therefore, circular cities, which are based on the sustainable resource management, should be applying 4R principle for the waste management.

4R principle makes waste management more complicated compared to the conventional waste management with ultimate disposal. Waste generation should be reduced at source at the first stage of waste management hierarchy, or the reuse of sources should be considered. For IWM, waste separation and collection enter the waste management system and different alternatives could be optimal depending on the region. Since waste streams will be segregated to be sent to the proper recycle/recovery facilities, collection and separation becomes a significant step of IWM in circular cities. Separation at source or at transfer stations is also another question that is to be decided for circular cities. Recycle/recovery of waste can take place in Material Recovery Facility (MRF), Waste to Energy (WtE), Waste to Heat (WtH) and, compositing facilities. Various types of technologies could be used for recycle/recovery of waste. Therefore, transition to circular cities requires to analyze technical, economic, environmental and social aspects of each stage shown in Figure 1 and to make decisions for the relevant issues. Several factors influence these analysis and decision processes, that is why decision-making methodologies and their complementary tools serve for the process of transition to circular cities.

3. Circular City

Natural life continues as a cycle and this cycle can be named as cradle-to-cradle (McDonough & Braungart, 2002). Carbon, nutrients, energy, water move in a cycle and do not loss in the transformation processes.

A serious amount of resources are used for anthropogenic activities and converted into waste at the end of their life time as leaving their way out from natural cycle. Since the consumption rate is higher than their biodegradation rate or the materials are converted into products which cannot decompose in the nature, carrying capacity of nature is frequently exceeded.

More than half of the total world population live in the cities, and it is projected that this ratio will increase to 66% by the year 2050 according to UN estimates (World Economic Forum, 2018). Cities are places with high demand of resources due to high population, urbanization, and economic activities and where the resources converted into vast amount of waste to be managed. In other words, cities are important points leading to resource depletion and environmental problems. This also make cities available points to apply CE principles and reach the target of transformation to CE (Cavaleiro de Ferreira and Fuso-Nerini 2019). Concept of "Circular City" was born with the application of CE actions in the cities. Main purpose of circular city can be defined as managing product-waste relationship to prevent/minimize occurrence of wastes with efficient 4R methods in cities with high urbanization rates. In this understanding, materials flow continuously in a cycle and energy consumption is decreased as a result of decreasing single use with 4R applications (Gupta et al. 2004). Circular city should be self-sustainable (Gravagnuolo, Angrisano, and Girard 2019). Traditional way of cities to deal with products is linear. The linearity is defined with import-use-dispose steps. Linearity is in one-way direction; products are produced, used and disposed. Environmental concerns, material losses and economic losses were occurred with the waste (Gupta et al. 2004).

Circular city is identified as "a new sustainability paradigm" (Geissdoerfer et al. 2017). Sustainability is achieved by circularity. Turning cities to circular cities occurs in many countries. Between years of 1997-2001, in Japan, Eco-Town Program was developed and established in 26 cities. The program was aimed economic and environmental benefits. The program supported recycling projects with/without government incentives. Around 168 recycling facilities were built within the scope of the project (Van Berkel et al. 2009). In China, CE term was accepted in 2002 to provide closed loop of material flows. China had challenges about policy, technology and public participation. Policies in China were not enough to promote circular city adequately like low resource taxes and higher corporate value-added taxes. Public participation was not enough because of lack in the institutional capacities and awareness-raising activities related to the CE concept that encourage public participation (Geng and Doberstein 2008).

Cities will be improved in environmental and economic areas. Sustainability of materials will be achieved. Resource and energy consumption of urban areas are 75% of global consumption and urban areas are responsible for 80% of carbon emissions (Muñoz and Navia 2021). Implementation of CE at city level is one of the most challenging issues; however, cities are playing the key role for the transition from linearity to circularity hosting waste management activities (Muñoz and Navia 2021). CE strategies are mostly focusing on waste management which is compatible with resource recovery. Urban planning, urban design, sustainable development, system thinking and complex systems are very critical aspects that should be considered for circular city planning (Bibri 2018). When the basic components of IWM for circular cities such as waste generation/reduction/reuse at source, waste collection and separation at local level and waste recycle/recovery facilities at national level are considered (Figure 1), it is clear that transition to circular cities requires detailed social, technical, environmental and economic analysis in order to make decisions for planning, designing and operation of the facilities and monitoring their performances. Therefore, developing roadmaps towards the future plans for the transition to circular cities can benefit from decision-making methods and possible complementary tools to conduct detailed analysis needed for decision making (Figure 2).

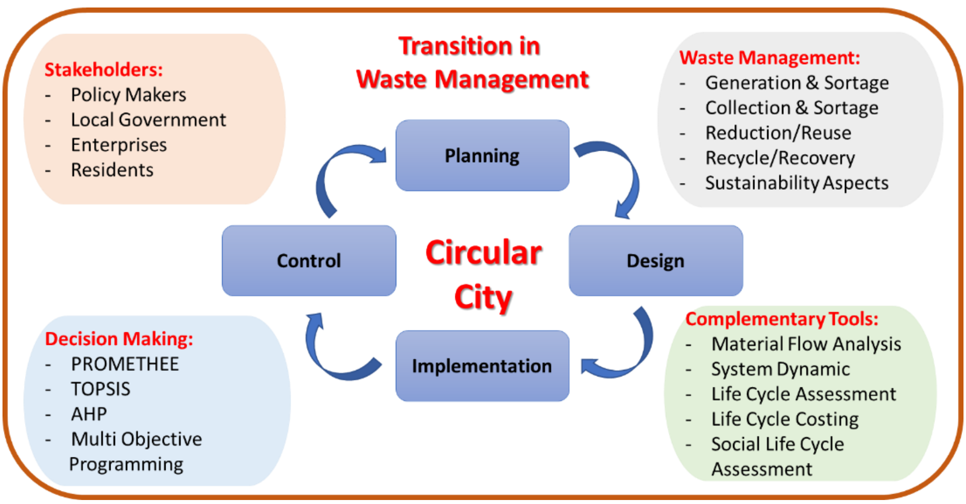

Figure 2. Major components of waste management in transition to circular cities.

MFA and SD are useful for the planning of the IWM strategies, designing of the facilities and measurement of the progress in circularity at city level, however, LCA provides a deeper understanding for the environmental impacts of the implementations. Sustainability assessment of circularity is lacking in the application level and complementary of the tools are needed for the full assessment of circular city applications. Decision-making methods such as MCDA and mathematical optimization models can be used for the planning of the IWM strategies and for the performance assessment with sustainability and circularity indexes.

CE goes back to 1996 when "Closed Substance Cycle and Waste Management Act" was applied in Germany. At the beginning of 21st century, Japan and China inspired from these applications and established regulations to promote CE in their countries (Tang and Liano, 2021). It is expected that usage of big data and data mining applications will accelerate the adaptation of CE to the linear cities.

4. Decision Making Strategies for Roadmap of Waste Management in Circular Cities

Decision making is a process of evaluating the candidate(s) for a specific purpose. Details of the specific purpose like its characteristics and relations within and out of the boundaries and necessary data for the candidates are the major components of the decision making. Since making relations with the specific purpose and the candidates are usually complicated due to the presence of various aspects, both qualification and quantification of this relationship is crucial for decision making. There are several established methods such as multi criteria decision analysis (MCDA) and multi-objective mathematical models. Multi-objective mathematical models including integer programming and other optimization techniques are beneficial in the case of available data and provides the selection of optimum alternative at the end of the solution of complicated mathematical equations. MCDA is beneficial for the cases which are affected by several factors and are lacking necessary data. MCDA relies on the determination of the factors which are effective on decision, listing the alternatives and assessing each alternative based on the determined factors. MCDA provides systematic thinking and clear picture of the importance weights of the factors. Analytical Hierarchy Process (AHP), TOPSIS, PROMETHEE are widely used MCDA methods. Their applications are well known and easy for the decision making in various areas. These methods are also demonstrated to be efficient for different types of environmental issues such as waste management. Lately, they are being used in the studies about the transition to circular cities. Since MCDA allows to consider all the required decision criteria, usage of MCDA for the decision of waste management strategies during the stage of transition to circular city can also enable to choose a sustainable alternative due to including technical, financial, environmental and social factors. Application of sustainable waste management to end-of-life of a product ends up with positive impacts on economy, human health and environment.

Waste handling processes usually have many alternative technologies and various combination of waste material can be used for an efficient recovery. Therefore, decision making methods are widely used for waste management issues. When the waste management concept for circular cities is considered, decision making methods can be used for planning and operation stages of MRF, WtE, composting or WtH facilities. Decision making methods serve as decision support tool for the planning of waste management strategies, selection of technologies or the location of plants. For circular city adaptations, decision making methods can also support the decision on waste stream combinations in the city context. Moreover, MCDA tools are useful in the case of data gap that is beneficial for newly adapted circular city applications.

Waste collection and shortage are usually optimized with decision making mathematical models which can contribute to the planning stage of circular cities where wastes are collected and distributed separately to recovery facilities. Multi objective distraction method is used for the optimization of waste collection routes and the efficiency of the model demonstrated in terms of its social, economic and environmental consequences (Mostafayi Darmian, Moazzeni, and Hvattum 2020; Tanhaie, Rabbani, and Manavizadeh 2020). Pluskal et al. 2021 proposed a method by using multi-objective strategy to make strategic decision for separation, sorting and recycling of paper, plastic, glass and mixed municipal waste. They demonstrated their methods with presenting waste separation, waste collection, network flow, sorting lines and recycling, reverse flows, multi-commodity problem, WtE plants and landfills sorting lines and allocation of waste types to different recycling facilities for Praque. Pérez et al. 2021 used Chosen by Advantages method to select the proper policy for curbside collection in a city in Canada. Pazouki et al. 2015 used bi-objective optimization model to minimize the cost and greenhouse gas (GHG) emissions sourcing from transfer stations.

During the planning and implementation stage of circular cities, MCDA is crucial in order to determine the most proper technologies for different waste recovery processes. Vlachokostas 2021 reported 153 published articles on WtE studies which are using MCDA as a tool. Analytical Hierarchy Process (AHP) is the most commonly used one which is used for 63 real case studies, mostly for anaerobic digestion and incineration. They highlighted the role of MCDA for decision makers in terms of giving holistic decisions, adapting to local solutions and easiness for real case applications. MCDA is also proven to be very efficient for developing countries such as Pacific Small Island Developing States (Joseph and Prasad 2020), Omman (Qazi, Abushammala, and Azam 2018), Nigeria (Alao et al. 2020) where data limitation could be a problem.

Bio-economy is one of the significant components in circular cities and there are various studies developing decision support tools for bio-waste treatment in the context of bio-economy in circular cities (Boffardi et al. 2021; Faraca, Tonini, and Astrup 2019; Diamantis et al. 2021; Soto-Paz et al. 2020; Iacovidou and Voulvoulis 2018) These studies could quantify the social, economic and environmental aspects allowing to make necessary comparison for different options based on the priorities of stakeholders.

Recovery of the end-of-life products, especially plastics and e-waste, is another major issue for the circular cities. Selection of the best practicable technology is essential for the planning stage of circular cities. Deshpande et al. 2020 proposed an approach to select the most sustainable end-of-life alternative for waste plastics by using MCDA. Fishing is very common in Norway and in the transition of circular city, they need to find how to recover fishing gears in a sustainable way. Mazlam, Yussof, and Mamat 2019 used AHP to evaluate end-of-life vehicle management systems. Management responsibility, performance management, capacity management, resource management, stakeholder’s responsibility, education and enforcement, improvement & enforcement, cost management are determined as key indicators for this assessment.

In addition to particular recovery sectors, overall waste management strategy of a circular city can also be evaluated with decision making methods. There are successful examples which provide decision support for the adaptation to be a circular city with sustainable solutions for developing countries (Yee Van Fan et al. 2021; Ferronato et al. 2019; Lindfors et al. 2019; Coban, Ertis, and Cavdaroglu 2018; Mir and Padma 2016; Josimović, Marić, and Milijić 2015). These decision support studies can assess potential, performance and feasibility of urban solutions by using MCDA method which allows the usage of technical, environmental and economic criteria. They demonstrated that the method works well for multi-functional urban solutions and eliminate the need to assess each function separately and their contribution to overall system. Also, methods are flexible to adopt new key areas or indicators and different demonstration of the results. Considering the uncertainties in the decision process, usage of fuzzy logic is preferred by Huang et al. 2020; Govind Kharat et al. 2019; Arıkan, Şimşit-Kalender, and Vayvay 2017. They used fuzzy MCDA to select the most environmental friendly IWM strategy. Fuzzy delphi is used to obtain the criteria, fuzzy AHP is used for giving priority weights for the criteria and fuzzy TOPSIS is used for the selection process. Fuzzy MCDA is provided to enhance the objectivity of the assessment for the uncertain cases. Real case application showed the efficiency and case independency of the method. Multi objective programming is used as a decision support system for IWM in the transition to circular city (Šomplák et al. 2019; Zhu et al. 2020).

Decision making methods can be used for the social assessment of the issues related with transition to circular city. Giovani Palafox-Alcantar, Hunt, and Rogers 2020 combined MCDA with hybrid game theory in order to improve stakeholder engagement in circular city applications. Since circular city has stakeholders from different sides and they may not have common purposes; there is a need to create optimum common benefits. The method is successfully applied for a WtE facility in UK. Yin et al. 2021 used two stage multi objective programming to handle the conflicting expectations between economic and environmental aspects. The results of the proposed method facilitate the conflicts for local authorities since they can provide waste flow allocation pattern and facility expansion capacity. Opening new job opportunities is a significant factor for social assessments and it usually lacks for most of the studies. Rabbani, Heidari, and Yazdanparast 2019 used multi-objective mathematical programming to assess the waste separation and transportation in circular cities.

Decision making methods are very suitable for coupling with other types of assessment methods since they consider several factors in the decision-making process and they may need to be evaluated specifically in depth. One of the most common combination is with LCA which is used to determine the environmental impacts of processes/products from cradle to cradle. Pauer, Wohner, and Tacker 2020 combined LCA-LCC and MCDA for the evaluation of food waste packaging system for ketchup. Environmental and economic analysis were conducted with LCA/LCC and TOPSIS is used for the selection of the optimum system. Stone, Garcia-Garcia, and Rahimifard 2019 combined MCDA, cost benefit analysis (CBA) and LCA to select the most sustainable strategy for food waste valorization. MCDA can also be used for interpretation of the LCA results (Zanghelini, Cherubini, and Soares 2018; Renzi, Leali, and Di Angelo 2017). Although LCA provides a comprehensive result set for environmental facts, interpretation of the results for decision-making can be difficult. Therefore, combination of LCA with MCDA tools are beneficial. MCDA provides the ranking in spite of conflicting preferences based on different criteria in LCA. One of the assertive studies is conducted by Roberts et al. 2018 who proposed a software (SWIMS) which is a dynamic life cycle based optimization and decision support tool for IWM. Economic and environmental aspects are calculated based on LCA by using nonlinear expressions including the waste type and handling process. SWIMS provides the required capacity for the facilities and supports decision makers for the upgrading and alternative infrastructures for meeting the capacity. Authors pointed out that SWIMS is proper by the aim of understanding the adaptation requirements of the cities to circular city concept.

MCDA is widely coupled with GIS for making contribution to waste management strategies by supporting the location settlement. Moore et al. 2020 combined MCDA, geospatial analysis and MFA in order to evaluate alternative reuse strategies for lithium batteries of electric vehicles. Geospatial analysis is used to find optimal transportation routes and MFA provided the availability of batteries in the regions. This method is useful to show the properness of the CE strategies in terms of resilience and sustainability. Alikhanov et al. 2021 used geospatial analysis and MCDA with a multi-objective approach to select the best alternative for waste collection for a big city in India. Waste collection is an important component for circular cities since 4R activities requires an extended transportation compared to conventional disposal ways. They suggest the mentioned method especially to developing countries, where the data could be lacking. Asefi and Lim 2017 used TOPSIS in GIS environment and used mixed integer programing to minimize environmental consequences and costs in order to develop the optimum IWM system. Mixed integer bi-objective optimization model is used to define waste collection network by including several key point considerations. The decision for the disposal and recycling facility is made by using PROMETHEE II.

Other new approaches that could be helpful for the transition process to circular cities are MFA and MCDA combination and the concept of energy justice. Makarichi, Techato, and Jutidamrongphan 2018 highlighted the essence of MFA combination with MCDA for the efficiency assessment of IWM systems. MFA provides feedback for the improvement of the system and choosing the proper criteria for MCDA. This method is defined as a cyclic decision making for IWM. Fetanat et al. 2019 considers the application of an integrated multi-criteria decision-making model consisting of fuzzy decision-making trail and evaluation laboratory method, the analytic network process and the simple additive weighting approaches for the evaluation of energy justice. Energy justice is about the trilemma of energy security, energy poverty and climate change. The DEMATEL and ANP were used to determine the importance weight of the technology selection criterias in a fuzzy environment. The SAW method was used to select the most suitable waste-to-energy production technology.

5. Complementary Tools for Roadmap Studies

5.1. Material Flow Analysis

Material Flow Analysis (MFA) designates the sources, pathways and sinks of the material within a defined system to analyze the flux of each material in the whole system (Islam and Huda 2019; Brunner and Rechberger 2004). MFA includes the terms of processes, flows and stocks. Processes are transformation, transportation and repository of the materials. Flow is the pathways between the processes and stocks are the stored materials. Principle of mass conservation can be applied as a controlling function for the results of MFA; therefore, this definite characteristic of MFA makes it tempting for the decision support issues in waste management (Brunner and Rechberger 2004). Application of MFA to environmental issues goes back to 1970s. Metabolism of cities and the fate of pollutants in the watershed or urban area are the most common areas of environmental applications. Lately, MFA has been used for different purposes in the area of developing roadmaps for waste management strategies like estimation of waste amount and type, assessing the performance of waste management strategies and supporting strategic waste management planning etc. (Tran et al. 2018).

The basic function of MFA for waste management is the calculation of waste amounts and waste streams to be used for directing the waste compositions to alternative recovery/reuse/recycle streams and to alternative technologies respectively. Secondly, it provides to design and check process efficiency for recovery technologies. Thirdly, environmental impacts of waste management facilities can be evaluated with MFA. Therefore, MFA can be crucial for the planning, implementation, operation and controlling stages of waste management in the transition phase to circular cities. MFA can also be coupled with other complementary tools such as LCA due to its ability to provide data.

MFA is very useful for the planning stage of transition to circular cities since it provides the material flow which can be used for determining the system boundaries with maps including waste flow (Brunner and Rechberger 2004). For example, Camilleri-Fenech et al. 2018 preferred MFA in order to make material balance to allocate the waste streams to the alternative municipal waste management applications in the Maltese Islands. So, it was used to observe change in the waste flow in a period of time and to make a projection at the future time that are helpful for development of roadmaps for the transition stage of Malta to being a circular city. In the planning stage of transition to circular city, MFA can be used for the prediction of physical composition of MSW and it is demonstrated that MFA is capable of predicting physical composition without a need for sampling and analysis (W. Jing Wang and You 2021).

MFA is used as a tool to measure the level of CE by providing the data for recycle capacity at city level. Potential of PET, PVC and PP recycling at Europe level is calculated based on MFA (Eriksen et al. 2020). Haas et al. 2020 proposed a method to evaluate the reuse potential of tunnel excavation material by using MFA. Huuhka and Kolkwitz 2021 demonstrated that MFA can be used to make the inventory of existing buildings for urban planners in order to make the strategic planning for the reuse and recycling of demolishing waste in the renovation and replacement of buildings.

During the transition stage to circular city and afterwards, MFA can be used for providing data to find practical solutions to prevent toxic emissions and valuable materials to be discarded (Hai, Hung, and Quang 2017). For example, Tran et al. 2018 used MFA to analyze the flow of waste TVs (reuse, recycle, disposal) from households in urban areas of Vietnam and concluded that 25% of precious metals were discarded. Not only the material balance, energy and emission balances are also included in some studies. Sharma and Jain 2020 used MFA to calculate material, energy and emission flows and they concluded that material was saved at 2-6% on the contrary to the energy and emissions in the case of recycling. This recognition is valuable to convert this unrecycled fraction to the CE in the implementation stage of circular cities. Also, determination of the existing situation in terms of circularity is beneficial to develop the roadmaps for the improvement of circularity. Lu et al. 2021 used MFA to propose “Industrial Symbiosis System Waste Flow Metabolism Analysis” which is aimed to design efficient industrial symbiosis at city level for the CE and provides to measure circularity. Elgie, Singh, and Telesford 2021 developed a methodology to measure the circularity of waste management on the basis of resource flow by using MFA. Tanzer and Rechberger 2020 proposed two simple indicators for the circularity assessment of complex systems that are derived from MFA. Camilleri-Fenech et al. 2018 declared that MFA is also provided to evaluate the circularity of Malta and efficiently helped for waste management strategy. Tazi, Idir, and Ben Fraj 2021 used MFA to make an assessment of residential buildings for the recovery of aggregates and to adapt to the circularity of the city. MFA is proved to be supportive for the optimization of material flow in the context of reverse logistic. Circularity assessment is beneficial at both planning and implementation phases for circular cities in order to select the most sustainable waste management strategies and to monitor the efficiency of being a circular city.

MFA can be used for the roadmap of waste collection and sorting in the circular city since it determines the waste flow. Dzhuguryan and Deja 2021 proposed smart supply chain for the integration of municipal solid waste management and industrial waste in the concept of multi-floor manufacturing by using MFA. Kleinhans et al. 2021 used MFA to evaluate the household package sorting facilities. It is known that recycling efficiency depends on the proper sorting and this method can support decision making on waste management strategies and design of recycling facilities.

MFA is used in a few studies for the optimum design of waste disposal sites such as bioconversion technologies. Zziwa et al. 2021 used MFA for the efficient design of vermicomposting of pineapple for their recycle in the agricultural application. Guo et al. 2016 used dynamic MFA for the design of food waste bioconversion technology for the efficient recovery.

Transition to circular cities requires social and economic assessments, as well. Fuss, Barros, and Poganietz 2021 used MFA analysis to calculate waste allocation in order to understand the contribution of waste pickers to the circular city implementation and to provide socio-integration. MFA is used for the policy making of phosphorus flow in agricultural applications and waste in many studies. Biswas Chowdhury and Zhang 2021 and Wan and Yang 2021 proposed geo-environmental pressure assessment index by combining MFA and ecological indicator to understand the stability of the region under certain waste management applications. This could be helpful at city level region planning. Ohno et al. 2021 used MFA as a basis for GHG calculation to assess the recovery technologies in terms of the effects of recycled products on carbon sequestration.

Usage of MFA for plastic waste management is rare compared to other waste component (Chu et al. 2021) and there are a few studies on the stocks and flows of plastics in regional scale (Kuczenski et al. 2014; Xiao et al. 2020; Rochat et al. 2013; Ciacci, Passarini, and Vassura 2017; Chu et al. 2021; Li et al. 2020; Govind Kharat et al. 2019).

One of the most successful applications of MFA is in the area of e-waste management. E-waste is a dramatically increasing waste stream and having potential to pose environmental risks. On the other hand, e-waste is a critical waste stream for circular cities due to its high potential for resource recovery including rare earth elements, precious metals and ferrous metal. MFA is used for the identification of the ingredients, their amounts, the material and process flows in the reverse supply chain within the e-waste management system (Islam and Huda 2019). Therefore, MFA is a beneficial complementary tool for e-waste management in the context of CE. Islam and Huda 2019 showed that MFA is used as a tool in 55 of e-waste management studies in the literature and 84% of them are national/regional based. MFA can be functional in the planning and implementation stage of e-waste recycling in the circular studies. Prediction of the e-waste production and their potential material recovery can be used in the planning stage of circular cities. MFA can contribute to the implementation stage of circular cities with material flow and stock estimation. Mohammadi, Singh, and Habib 2021 used MFA to support the decision-making for the best alternative e-waste management at island regional level. Jia et al. 2021 used MFA to calculate the volume of high-tech minerals in cell phones in order to present data for the recycling industry.

MFA is functional in terms of designation to explore the flows of material (Williams, Kahhat, and Kaneko 2012; Tran et al. 2018). MFA is demonstrated as a successful tool in terms of providing transparent and systematic results. MFA can be more preferable in the case of limitations in data instead of LCA; however, it should be complemented with a suitable tool that can analyze environmental impacts Tran et al. 2018 and Sevigné-Itoiz et al. 2015 demonstrated that MFA can be coupled with consequential LCA (CLCA) studies for a more efficient GHG emission calculations. Since CLCA aims to calculate GHG emission and MFA is based on the material flow and balance analysis; MFA is a good complementary for LCA studies. Using MFA as a complementary tool to LCA could be useful to determine the sustainability of the waste management in addition to the circularity (Boldoczki, Thorenz, and Tuma 2021). Results of MFA is fed to LCA and it is concluded that recycle of washing machine increased the circularity based on MFA. However, environmental impacts are not prevented and sustainability of the waste management strategy for washing machine reuse were low. Istrate, Galvez-Martos, and Dufour 2021 combined MFA and LCA in order to evaluate alternative MSW management strategies and demonstrated that MFA is a perfect base for LCA studies for the cases of alternative evaluations. MFA was efficient to make material mass balances in order to understand if the proposed alternative is efficient for reducing the landfilling and LCA provided the information for environmental impacts. Mousavi, Ventura, and Antheaume 2020 combined MFA with LCA to calculate the potential amount of aggregates on the regional scale and to assess the environmental impacts. (Ng and To 2020) combined MFA and LCA in order to assess the alternatives for household waste including waste and energy, waste to energy and reduction. MFA is already one of the most commonly used techniques for the waste management assessment (Campitelli and Schebek 2020). MFA was used as data for LCA. MFA was made for waste paper and it quantified with LCA (Sevigné-Itoiz et al. 2015). Arena and Di Gregorio 2014 combined LCA results and MFA to compare alternative waste management studies. This combination is highly valuable for combination of MFA and GIS provided to calculate demolition waste at city level and to develop a multiscale spatial map (D. Lu et al. 2021). These maps are providing the amounts of waste for each component and the addresses for resources and sinks.

5.2. System Dynamics-Based Approach

System dynamics (SD) is a methodology which is used for solving problems related to simple and complex systems by analyzing their components considering cause-effect relations and feedback loops. Thus, it has a very wide application area covering different sectors. SD provides the analysis of the complex systems by defining their components, their relations and behavior. In addition to quantification and simulation, SD provides system archetypes, Causal Loop Diagrams (CLDs), and Stock and Flow Diagrams and supports the sustainability (Nabavi, Daniell, and Najafi 2017). There are various studies in the literature to support waste management decisions in regional context in terms of economic, social and environmental aspects. This approach is used for the issues related to waste reduction, generation, source separation, waste recycling and recovery and waste disposal (Berenjkar, Li, and Yuan 2021) which are essential components of transition to circular cities. Setting goals for waste management and understanding the effects of amendments in the system are the vital advantages of SD applications for waste management that provides comprehensive understanding of the system. Therefore, SD is one of the beneficial complementary tools for the development of roadmaps towards future planning of circular cities due to its ability answering what-if questions with system simulation.

SD approach is used in order to analyze waste generation, reduction, collection and sorting activities for different cases that contributes to the decision making in the planning and control stages of transition to circular cities. Ding et al. 2021 modified SD method to an agent-based model which allows to define each stakeholder in the system individually and provided an accurate estimation of waste generation in China. Chengpeng Lu et al. 2021 used SD in order to predict the waste generation based on social factors including gross domestic product (GDP) growth, total population, population growth, MSW generation per capita, and MSW generation charges. In addition to MSW generation, they could calculate GHG emissions and economical aspects to support decision making for the most sustainable strategy and demonstrated that SD is a promising approach for waste management applications. Ruiz Galeano and Bautista Rodríguez 2021 used similar approach to predict mobile phone waste generation and GHG emission depending on their lifetime by using the variables of mobile telephone line acquisitions, gross domestic product per capita, and the lifespan of mobile phones. W. Jing Wang and You 2021 used SD approach to calculate the effect of waste classification on waste management applications in terms of economy and environment and contribute to the sustainability assessment of the cities. de Lorena Diniz Chaves, Siman, and Chang 2021 analyzed the proper waste streams from household and industries for (RDF) in terms of cost, benefit and risk aspects by using SD approach to support policy making decisions. Results of this study demonstrated that SD based approach provides the data for the case of pessimistic and optimistic situations and let the system uncertainties manageable. They suggested to include the location optimization of RDF facilities and the determination of the possible waste materials with high calorific value. Based on the review of this chapter, MFA would be suggested as supportive to SD approach for these aspects; since MFA determines the sources, flow and stocks in depth in a defined system boundary.

SD approach can be used for evaluating whole municipal solid waste management systems to provide data for the selection of most efficient strategy which could be beneficial for all stakeholders in the phase of transition to circular city as shown in Figure 2. Babalola 2019 investigate food and biodegradable waste management alternatives. Zhu et al. 2020 conducted similar study for food waste management; however, they focused on optimizing food waste management fee for stakeholders. They pointed the limitation of the method as the constant food waste amount for each restaurant. In the light of this chapter, integration of MFA to this method could be suggested to improve their proposed method. Guzzo, Rodrigues, and Mascarenhas 2021 developed a CE transition model for e- waste that includes the determination of the flows in nation-wide and simulation of transition scenarios. This model provides decision support for the authorities to test different transition strategies in advance. Technological factor, administrative factor, socio-economic factor and demographic factors can easily be analyzed by using this method in terms of their effect on GHG emission from waste management facilities. Xiao et al. 2020 used SD for analyzing the effects of waste management politics in Shanghai where certain politics are applied for waste management, and this study is different from others by including production, sorting, collection and final treatment all together.

Besides providing data for the selection of the most efficient waste management strategy, usage of SD approach can provide a closer look on special wastes and specialized management for different waste categories. These studies are especially helpful for the enterprises which plan investments in circular cities. B. Zhang, Li, and Yue 2020 made a detailed assessment of battery recycling including the process of sorting, application technology and replacement at company level in order to increase profits and recovery rate. Pinha and Sagawa 2020 proposed a model which support public managers to decide the alternative waste management strategies with a comprehensive content of sources and flows and financial analysis by using SD. Y. Wang et al. 2020 used SD to analyze the alternative strategies for PET recycling and suggested the optimal alternatives and the improvements for the others, as well.

In addition to technical and financial analysis, environmental and social analysis are a must for the sustainability assessment. Usage of SD approach in the assessment of new waste management strategies can provide the environmental and social analysis that could be helpful for the planning and control stages of transition to circular cities, especially for policy makers and enterprises, to evaluate the sustainability aspect. Can Lu, Li, and An 2020 used SD approach to calculate GHG emission evaluate the effect of population size, policy for charging and incentives and emission reduction policies. Xiao et al. 2021 combined SD with Logarithmic Mean Divisia Index to determine the incentive forces for GHG emissions from waste. Social analysis is usually a though section for sustainability assessment due to the need for the analysis of behavioral parameters for the consumers (Zhu et al. 2020). Lately, the combination of SD method with game theory applications are applied for the social analysis efficiently which could be highly beneficial for the sustainability assessment of transition to circular city. Yu et al. 2020 coupled evolutionary game theory with SD approach to analyze the potential conflicts for the incineration plants between stakeholders such as enterprises, local government and residents in the region in order to understand the effect of evolutionary stability strategies. Governmental incentive and legal punishments were tested. Legal punishments demonstrated as efficient incentive forces for solving the conflicts. Du et al. 2020 used the similar approach for C&D waste to analyze stakeholders' decision-making behaviors in C&D management. Yang et al. 2021 used dynamic evaluation game theory in order to understand the willingness of the consumers to participate in packaging waste recycling depending on advertising, governmental policies and waste system efforts and they concluded that advertising and governmental policies are positively correlated with the participation.

To sum up, benefit of SD approach is to include complexity and dynamic nature in the modelling. Identification of the variables in the system, defining and quantification of the relations and validation are the basic steps of SD approach. SD approach is useful to simulate the alternative scenarios and the proposed regulations in terms of technical, financial, environmental and social aspects for decision support and highly recommended to be used for circular city implementations. This method can be used as a future projection tool for reduction amount of emission, landfill, illegal dumping in terms of mass or volume (Ding et al. 2018; 2016). SD approach can contribute to developing roadmaps for transition to circular city due to its integration ability of physical models to solid waste flows with representations of dynamic behaviors and social norms (Guo et al. 2016).

5.3. Life Cycle Assessment

Life Cycle Assessment (LCA) is a methodology which is used for quantically analyzing environmental burdens of a product/process/service during its lifetime. Thus, it provides the opportunity of evaluation of environmental sustainability ‘from-cradle-to-grave’ in other words covering all of life phases starting from raw material extraction till disposal at the end of lifetime.

A LCA study consists of four iterative steps as Goal & Scope Definition, Inventory Analysis, Impact Assessment and Interpretation (ISO, 2006). As the sustainability has three pillars as environment, economy, and society, LCA approach is also used for assessment of the economic and social sustainability with specifically developed methods (LCC and S-LCA), which will be discussed at the following sections. Application of all these methods allows a holistic evaluation of sustainability namely Life Cycle Sustainability Assessment (LCSA) (UNEP, 2009), which can be used for evaluating the sustainability of circular economy solutions (Peña et al. 2021).

When the situation is to make a decision about waste management, one of the first questions to answer is the level of possible environmental impacts, which is also important for transition to circular city context. LCA deals with the evaluation of environmental impacts in various categories based on a scientific approach and it allows to make comparison of different options, which makes it a valuable tool for decision making processes. Besides comparing, LCA is found to be helpful and appropriate to be used in waste management with various aims. Clavreul, Guyonnet, and Christensen 2012 classified these in six main fields: understanding an existing waste management system; improving existing waste management systems; comparing alternative technologies/technology performance; technology development/prospective technologies; policy development/strategic development; and reporting. Here, two of these usage areas which are comparing alternative technologies/technology performance and policy development/strategic development will be discussed focusing on usage of the methodology at city level due to the scope of this chapter.

Comprehensive review of previous LCA studies on waste management pointed out that most of the studies were executed in developed countries especially in Europe (Laurent et al. 2014; Khandelwal et al. 2019). Municipal solid waste was the main waste stream focused and further studies are needed for more special wastes such as C&D, e-waste, etc. (Laurent et al. 2014). Since, municipal solid waste management systems are site specific systems, it is emphasized that a generalization of the studies is not possible and LCA will be a useful tool for allowing inclusion of local conditions i.e., waste hierarchy, waste composition, energy mix, etc. (Laurent et al. 2014; Khandelwal et al. 2019).

Choice of the most appropriate waste management option in terms of environmental burdens is especially a need for decision makers at city level who are responsible for the related services. Studies executed for this aim are good examples of LCA application for waste management with big capacity. In the studies executed by (Eriksson et al. 2005; Cherubini et al. 2009; Bovea et al. 2010; Antelava et al. 2019; Goulart Coelho and Lange 2018; Özer and Yay 2021; Richard et al. 2021) waste management options for different cities are evaluated using LCA methodology by targeting to determine the most environmentally sustainable option. It is important to state that these studies are just some examples of the topic, which is studied and developed through more than last two decades.

Eriksson et al. 2005 used LCA methodology for case studies for the cities of Uppsala, Stockholm, Älvdalen in Sweden. Mentioned case studies include landfilling, incineration, recycling of plastic, paper & cardboard and anaerobic digestion & composting as the solid waste management options. Landfill without any recycling option, landfill with electricity production using biogas, sorting plant combined with producing electricity & biogas and incineration options were investigated for city of Rome, Italy and analyzed in term of global and local emissions, total material demands, total energy requirements and ecological footprints (Cherubini et al. 2009). Different ratios of selective collection of recyclable solid wastes (paper and cardboard, glass, packaging materials), composting and biogas production options, landfill with or without energy recovery, different waste collection systems were the varying parameters of scenarios developed by Bovea et al. 2010 for the evaluation of solid waste management practices for Castellón de la Plana, Spain using LCA. Solid waste management options for London, UK evaluated by Antelava et al. 2019 firstly starting with the ongoing application (materials recovery + incineration) as a base and then including low temperature pyrolysis (LTP) reactor and a hydrogenation reactor (VCC) as two different options for plastic wastes collected and landfill as a third option. Goulart Coelho and Lange 2018's study investigated the most promising solid waste management option for Rio de Janeiro, Brazil using LCA-IWM methodology for eight different scenarios which include different waste collection methods, materials recovery and energy production accompanied by evaluation of the current waste management strategy. Different waste management strategies leading to energy production from waste is evaluated for Kırklareli, Turkey. The ongoing waste management method which is landfilling and electricity production was the base study and it is compared with the suggested waste management strategy: a combination of mechanical separation, bio-mechanization, landfilling and higher amount of electricity production (Özer and Yay 2021). Richard et al. 2021 analyzed three different waste management scenarios using LCA methodology for Arusha, Tanzania as recycling and landfilling as the baseline, recycling + landfilling + composting as the second scenario and recycling + landfilling + anaerobic digestion as the third scenario.

Recycling and resource recovery systems developing, waste management understanding is changing, and it seems that the options and achievements will also develop related to them in the future. Thus, LCA is also used and valuable to evaluate the environmental sustainability of recycling and resource recovery systems to understand their environmental performances since unintended environmental burdens may be higher than disposal options depending on the processes applied.

Especially, recycling of plastics, its efficiency and environmental impacts are important topics considering the serious plastic pollution problem that humanity face nowadays and their key role to have circular cities. LCA is used also for evaluation and decision-making about plastic waste management systems (for a review, see (Antelava et al. 2019)). For example, Rigamonti et al. 2020 compared a baseline scenario (incineration with energy recovery + mechanical biological treatment) with 4 different plastic waste management scenarios (source separation for material recycling; source separation for material upgrading and separation into specific polymer types; source separation with metals; mechanically separation before incineration) using LCA. Khoo 2019 used LCA to determine the most appropriate one of 8 scenarios of plastic waste management options (gasification, mechanical recycling; pyrolysis, waste-to-energy through incineration) for Singapore. Jeswani et al. 2021 compared pyrolysis to recycle mixed plastic waste with its conventional alternatives, mechanical recycling, and energy recovery, using primary data collected from industry. Besides known recycling and recovery processes, researchers also used LCA to measure environmental performances of novel products as substitution of existing plastic products such bioplastics (for a review, see (Bishop, Styles, and Lens 2021)) and novel recycling and recovery processes and products (Gear et al. 2018; Horodytska, Kiritsis, and Fullana 2020; Ahamed et al. 2021; Goglio et al. 2020).

Another important waste stream is electronic waste (e-waste) since being produced in high volumes, being harmful for the environment due to its toxic content, requiring complicated and costly processes of waste management due to its content and complexity, causing resource depletion of rare elements (critical raw materials) and constituting an important source of resource recovery for circular cities. LCA is also used for evaluating waste management systems of e-waste (for a review, see (Ismail and Hanafiah 2019)), end-of- life (EoL) alternatives for e-waste (for a review, see (Xue, Xu, and Zhang 2019)) and assessment of novel recycling and resource recovery technologies (Villares et al. 2016; Raugei and Winfield 2019; La Rosa et al. 2021).

5.4. Life Cycle Costing

Life Cycle Costing (LCC) is a methodology which is used for evaluation of cost of a product/process/service through its lifetime with a cradle-to-grave approach. Thus, costs are evaluated starting from raw material extraction phase until final disposal. LCC also can include the cost of externalities (França et al. 2021) through environmental LCC and societal LCC which evaluate monetary value of environmental and social impacts (La Rosa and Ramakrishna 2021). Since, circularity applications generates transport of materials and products through different product systems, economic evaluation of these activities requires higher attention to include all possible economic impacts as well as environmental ones to prevent burden shifting. Thus, LCC is an appropriate method allowing this evaluation for across different sectors including external costs (La Rosa and Ramakrishna 2021).

These characteristics make LCC a beneficial tool for evaluating waste management options of cities and it is generally used as integrated with LCA (for reviews, see (Martinez-Sanchez, Kromann, and Astrup 2015; Medina-Mijangos and Seguí-Amórtegui 2020). Reich 2005 used LCC and environmental LCC for evaluating economic performances of municipal waste management system scenarios for three municipalities of Sweden: Uppsala, Stockholm, Älvdalen. Considered waste management systems include heat, electricity, nutrients, vehicle fuel, cardboard, and plastic production besides conventional waste treatment units. At environmental LCC part, external environmental impacts monetized through a weighting system based on damage assessment. Massarutto, Carli, and Graffi 2011 evaluated economic feasibility of different waste management options which include energy and waste recovery.

Food waste is also an important problem causing environmental pollution as well as generating serious amount of economic, water and energy loss considering embedded water and energy values of the products (De Menna et al. 2018). An important portion of food produced worldwide converts into food waste at production, distribution, and disposal phases, which leads to high amount of food waste ending up in cities. This is a problem to be solved at a transition to a circular city period. Various researchers used LCC for evaluation of food waste management options in cities in terms of their costs (for a review, see (Edwards et al. 2018).

Plastic waste is a waste stream with major importance for circular cities. Cost of recovering plastic waste is an important parameter to reach high recovery rates; thus its evaluation is essential for deciding appropriate methodologies besides environmental and technological assessment. Zackrisson, Jönsson, and Olsson 2014 studied environmental and economic performance of various methods for recycling plastic part of cables, which is not a common approach after recycling metal content of the cables, using LCA and LCC as a guide for the industry. Faraca, Martinez-Sanchez, and Astrup 2019 used LCA and LCC by the aim of evaluating different scenarios for recycling of hard plastic waste collected at Danish recycling centers. Mentioned scenarios included usage of mechanical and feed stock recycling systems as recycling options. Besides, energy, location of the recycling plants and final usage of the recycled content were evaluated. Joachimiak-Lechman et al. 2020 executed LCA & LCC for a recycling plant in Wielkopolska, Poland, which uses shredding, mixing and thermal processing as the recycling methodology. R. Zhang et al. 2020 used LCC combined with LCA to evaluate environmental and economic impacts of producing blanket from waste PET bottles.

The volume of C&D has a tendency of increase due to urbanization and urban transformation. CE actions for closing the loop for this type of waste in circular cities also require assessment of economic sustainability. LCC is used as a tool for assessing various parameters related to C&D. Mah, Fujiwara, and Ho 2018 used LCA & LCC to evaluate various C&D management scenarios for Malaysia by using primary data collected from seven different construction projects. In the scenarios, landfilling, recycling concrete at road construction site, recycling concrete at concrete batching plant options were included as waste management strategy. Li et al. 2020 investigated high-grade concrete recycling in terms its eco-efficiency considering environmental and economic aspects via LCA & LCC. Di Maria, Eyckmans, and Van Acker 2018 again chose using LCA & LCC together, for a comparison of down cycling and recycling of C&D as a support for policy makers.

5.5. Social Life Cycle Assessment

Social Life Cycle Assessment (S-LCA) is a methodology which is used for assessing the potential social and socio-economic impacts of products/processes through their life cycle, using quantitative and qualitative data.

Similar to LCA, a S-LCA study consists of Goal & Scope Definition, Inventory Analysis, Impact Assessment and Interpretation steps and it is an iterative method. In the Goal and Scope phase, main goal and scope, functional unit, system boundary and related stakeholders are defined. Inventory Analysis consists of defining inventory with the guidance of stakeholders which may be classified into five main categories as workers/employees; local community; society (at national and global levels); consumers; and value chain actors and may be expanded including other stakeholders (i.e., NGOs, public authorities, etc.) or subgroups depending on the study. Related impact subcategories are determined for each stakeholder group and qualitative and quantitative indicators are determined for each subcategory to constitute the inventory of the study (UNEP, 2009; UNEP 2020). Impact assessment is the phase at which possible social impacts are determined. Impact assessment phase of S-LCA is a controversial topic since measurement of social and socio-economic impacts is complicated, a common methodology is not decided and S-LCA is still its development phase (Yi Fan et al. 2015). With the latest guideline by UNEP (2020), impact assessment phase has a more comprehensive definition. Reference Scale Assessment & Impact Pathway Assessment are two main approaches used for Social Life Cycle Impact Assessment (S-LCIA) which are used for the aim of assessing social performance/risks and consequential social impacts, respectively. In interpretation phase, which is the last phase of the S-LCA method, results are reviewed, and conclusions and suggestions are produced by executing a deep analysis and discussion of the results. The outputs of this phase may be used for informing the stakeholders of the study and by decision makers.

S-LCA is a relatively new methodology compared to LCA and LCC, thus there are still lots of points to develop in terms of methodology and standardization. However, attention of researchers and the number of studies are increasing which is promising for its future use (for reviews on methodology and the historical evolution of it, see Huertas-Valdivia et al. 2020; Ramos Huarachi et al. 2020.

Social and socio-economic impacts of waste management systems are also important in terms of providing sustainability of the mentioned systems and so they should be included in decision-making process. The number of studies which use S-LCA methodology for waste management systems is relatively low compared to LCA and LCC studies due to being a nascent methodology. S-LCA is used with various aims related to *waste management* such as evaluating household waste management system (Azimi, Dente, and Hashimoto 2020), evaluating formalized recycling systems (Aparcana and Salhofer 2013a; 2013b), and municipal solid waste management systems in low income countries (Tulokhonova and Ulanova 2013; Ibáñez-Forés et al. 2019), evaluating packaging waste management systems for a metropolitan city (Yıldız-Geyhan et al. 2019); *waste recycling* such as evaluation of greenhouse gas emissions from waste-to-energy incineration (Can Lu, Li, and An 2020), evaluation of used polyethylene terephthalate (PET) bottles (Foolmaun and Ramjeeawon 2013), evaluation of phosphorus recycling (Teah and Onuki 2017), informal recycling of electronic ICT (Umair, Björklund, and Petersen 2015) and *product value chains* (Reinales, Zambrana-Vasquez, and Saez-De-Guinoa 2020).

CONCLUSION

Urban population has a historical evolution of continuous increase, and the population projections demonstrate that this trend will continue ending up increasing the problems of the cities face nowadays. This brought the idea of transformation of existing cities to Circular Cities analogous to circular economy by applying circular economy principles to urban environment. Application of CE principles in cities and transformation of existing cities to Circular Cities is a big challenge to achieve considering cities are living systems which are a combination of different subsystems with tremendous amount and type of flows.

Waste is an important flow in cities which must managed wisely to close the loop for reaching Circular City targets. In this study, after giving detailed definitions and explanations on the related terminology and Circular City concept, a comprehensive literature review on the latest scientific literature on the decision-making for waste management strategies for

Circular Cities accompanied by complimentary tools are presented and a framework of their application is summarized.

Decision making methods are beneficial and widely used by decision makers determining strategies for waste management systems in terms of planning, choosing appropriate technologies and location at plant or city level. Thus, they can be used also during transformation period of existing cities to Circular Cities or planning new Circular Cities. These methods allow handling complex combination and flows of wastes through circular city applications at different sectors. This is especially valid when decision-making methods are accompanied by various complementary methods to deal with different sides of the considered applications. Here, most widely used complementary tools for decision-making methodologies (MFA, SD, LCA, LCC, S-LCA) are presented in terms of their previous usage in waste management systems focusing on most important waste streams for circular economy and circular cities (plastics, e-waste, C&D and food waste). It was determined that combined usage of decision-making methodologies with these complementary tools can be applied to fill the gaps of one methodology with another and for a more comprehensive evaluation of the system studied to reach more effective results of decision-making process for circular cities. Each included tool has its own points to be developed in terms of methodology and also usage for waste management, circular cities and usage at city and intersystem levels. Besides, since Circular City applications require a holistic view and systematic thinking, combined usage of these tools is open to be developed with the purpose of usage for waste management system planning of Circular Cities.

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Chapter 19

ROLE OF MICROORGANISMS IN DEGRADATION OF HAZARDOUS SOLID WASTE

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ABSTRACT

Microbial biodegradation has been one of the alternate techniques of biodegradation over the last few decades since such degradation offers an efficient albeit greener route compared to other chemical methodologies relevant to this process. Not only the greener routes but also the efficient biocatalysis offered by the microbes has been another important chord of such bio-based processes. Thus, a review becomes worthwhile to enumerate such operations, from orthodox to progressive, for a successful adaptation of such a toolbox. In pursuit, herein an attempt has been made to review microbial degradation of waste, especially solid waste. Solid wastes encompassing generic wastes such as plastics, other polymeric throw-outs, and heavy metals which are often found in industrial sewage discharge, have been the classical solid burden on society. Moreover, chemical wastes such as pesticides, agricultural wastes as well as pharmaceutical wastes have been found as an incremental solid burden over the last few years. In this review, biodegradation arenas starting from orthodox components such as composting, biopiling, biosparaging, bioventing, bioenhancement and land farming to more contemporary approaches such as genome editing, system biological approaches, recombineering have been discussed in detail. Furthermore, exploitation of microbial enzymes such as Oxidoreductases, Microbial dehalogenases, phosphotrioesterases in solid waste management has also been taken into account. The specific applications of these approaches till date have been discussed which is expected to cast a light on various approaches on the microbial basis of solid waste management investigated so far. The academic niche of microbiologists, biotechnologists, bioprocess engineers as well as

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process chemists is expected to gain some insights from this review which may seed to explore further in this field.

Keywords:biodegradation, solid waste, biopiling, composting, genome editing, microbial enzymes

INTRODUCTION

The global environment was highly stressed by rapid urbanization, the industrial revolution, and tremendous population pressures on natural resources. Different unscientific activities of modern civilization generate a large amount of pollution waste (Banerjee et al. 2018a). Besides, overconsumption of raw material in large industries leads to the disposal in the environment of massive amounts of chemical contaminants and radioactive waste, which causes irreversible damage to the biosphere as a whole. Waste generation is the main driver of material and energy loss and raises environmental and social costs for collection, processing, disposal, and overall administration (Kar and Palit 2019). The generation of hazardous waste in India is directly linked to the country's economic growth. Cities and there is a lot of variety between them. If the pace of industrialization continues at its current level, it is expected that as the population grows, the amount of waste generated will grow as well, unless scientific waste management is implemented(Srivastava et al. 2015).In 2016, Bose et al. isolated two polyethylene degrading species *Penicillium chrysogenum* and *Penicillium oxalicum*from from the soil of the plastic dumping station. The degradation rate of HDPE was determined as 55.59% by *Penicillium chrysogenum* and 55.34% by *Penicillium oxalicum* in post 90 days of the incubation period.

The situation of waste management (WM) differs greatly between developed and developing countries, owing to the absence of adequate waste generation and disposal mechanisms in developing countries. As a result, WM has become extremely important and is given top priority as a result of growing concerns about environmental degradation and sustainability (Brewer and Sullivan 2003). Overflowing landfills, which are not only difficult to restore to a satisfactory state but also have grave environmental consequences in terms of soil and groundwater contamination and exposure to global warming, originate from uncontrolled, haphazard, and unscientific waste disposal on the outskirts of towns and villages.

The need for an efficient or operational WM framework is urgent, and it must be both economically and environmentally friendly. Several common WM and treatment approaches are used daily, including the following: (1) Incineration process: wastes and garbage products are stored at a high temperature in this method. (2) Sanitary landfills – this approach is more practical and commonly used around the world. Sanitary landfills are areas where garbage is kept apart from the rest of the world. (3) Recycling is the method of converting products into new types that can be used again. (4) Avoidance and elimination – avoidance entails the reuse of second-hand goods, the design of reused goods, and, in extreme cases, the use of recycled materials. So sustainably cleaning the contaminated atmosphere is very much necessary; in this regard, the position of microorganisms in WM and biodegradation of pollutants has escalated in recent years(Banerjee et al. 2018a). Various biotechnological instruments focused on micro-organisms such as bioremediation, biodegradation, bio composting and biotransformation have been used to rapidly build up and degrade an enormous amount of pollutants (Banerjee et al. 2018b). Cladophora sp. (green algae) has a high bioaccumulation capacity for toxic metals, according to Maghraby and Hassan, and can be used as a potent and alternative WM agent. Furthermore, microbial ecology is a critical element in the proper operation of biological wastewater (WW) treatment systems (Lake Mariut, Dahlia El Maghraby, and Hassan 2018). Martinez et al. (2018) show that archaea and bacteria predominate in WW treatment device bioreactors in Finland's polar arctic region. Nanoparticles are also being successfully used to improve the behavior of bacteria, a method known as nanobioremediation(Gonzalez-Martinez et al. 2018). Deinococcusradiodurans (extremophilic bacteria) is prevalent in the United States. Since it is a radiation-resistant cell, it is used in radioactive waste removal techniques and can normally tolerate radiation(Brim et al. 2000). As a result, using microorganisms in combination with various biotechnologies is the most efficient way for treating various wastes, as well as being eco-friendly, cost-effective, and environmentally sustainable.

Certain composting investigations revealed the influence of microbial inoculation on the compost quality as well. Usually, a significant reduction in the operation time (due to microbial action) of the degradation process, evidenced by a good quality compost (Abdullah et al., 2013andZhao et al., 2016). A study by Wei et al. (2019), investigated lignocellulose degradation to assess the effect of actinomycetes inoculation on the substrate (FW). The results showed that actinomycetes inoculation accelerated the production of the key enzymes, including CMCase, Xylanase, lignin peroxidase etc. and increased the rate of organic matter degradation. Manu et al. (2019), carried out decentralized composting of household wet biodegradable waste (HWBW) in the recycled plastic drums, inoculated with microbial inoculums. The added inoculum reduced the composting time period to 30–36 days and produced a pathogen-free compost.

The key goal of this chapter is to recommend and encourage the use of the most cost-effective and environmentally sustainable approach for handling polluted solid waste using various microbial agents in order to achieve environmental sustainability.

WASTE: A BRIEF OUTLINE

Human operation is the main cause of pollution. The created waste is complicated by the rapid and unplanned growth and alteration of lifestyle around the world. The biosphere as a whole is increasingly deteriorating due to the ongoing emission of toxic chemicals from various factories around the world. The rapid expansion of healthcare services and modernization of agriculture activities result in vast amounts of biomedical and agricultural waste, posing a threat to environmental health. Strong waste, liquid waste, and gaseous waste are the three primary categories of waste(Mondal and Palit 2019). Besides the various types of chemicals, plastic wastes from industries, hospitals and houses also pollute both the terrestrial and marine environment. Oceanic plastic debris exerts toxic chemicals, such as polychlorinated biphenyls (PCBs), nonylphenol (NP), organic pesticides, such as dichlorodiphenyltrichloroethane (DDT), polycyclic aromatic hydrocarbons (PAHs), polybrominated diphenyl ethers (PBDEs) and bisphenol A (BPA). These toxic agents have been linked to and are associated with many health problems, including developmental impairment (neurological impairment, growth abnormalities and hormonal imbalances), cancer, etc. Plastic ingested by some wild animals persists in the digestive system and can lead to decreased feeding stimuli, gastrointestinal blockage, and decreased secretion of gastric enzymes and decreased levels of steroid hormones, leading to reproduction problems (Hayden et Al. 2013)

CATEGORIZATION OF WASTE

Solid, liquid, and gas waste, as well as emitted heat, are indeed examples of waste. The source and characteristics of waste are used to recognize it. Waste items can be classified based on their origins and forms. Waste can be produced from four different sources in general:

Industrial, municipal, biomedical, and electronic are only a few examples. Waste can be graded based on its composition based on a variety of parameters, such as matter, degradation function, and so on based on the source and the environmental impact.

WASTE MANAGEMENT WHAT DOES IT MEAN?

WM essentially consists of waste storage, processing, recycling, and management. WM's key goal is to reduce the environmental and human health effects and impacts of waste. With rapid urbanization, the industrial revolution, and massive public pressure, this continues to be a growing problem, which puts great focus on the global climate. WM essentially consists of four pieces – Special policies are applied to all waste, manufacturing, electronic, municipal, and biomedical.

The basic concepts of WM have been extended to the 4R theory (refuse, minimize, reuse, and recycle). Waste generation, storage, processing, transportation, recycling, treatment, and disposal are all factors in India's waste management strategy. Landfills, incineration, composting, and gasification are some of the most widely used WM processes as described in Figure 1.

WASTE MANAGEMENT AND MICROBES

In WM, microbial biotechnology refers to the application of modern scientific methods and techniques to a broad range of microorganisms in a regulated environment without causing ecological disruption. Composting, biodegradation, bioremediation, and biotransformation are the most popular and effective WM methods used at different levels. *Bacillus* sp., *Corynebacterium* sp., *Staphylococcus* sp., *Streptococcus* sp., *Scenedesmus platydiscus*, *S. quadricauda*, *S. capricornutum*, *Chlorella vulgaris*, and others have all been used successfully for WM.

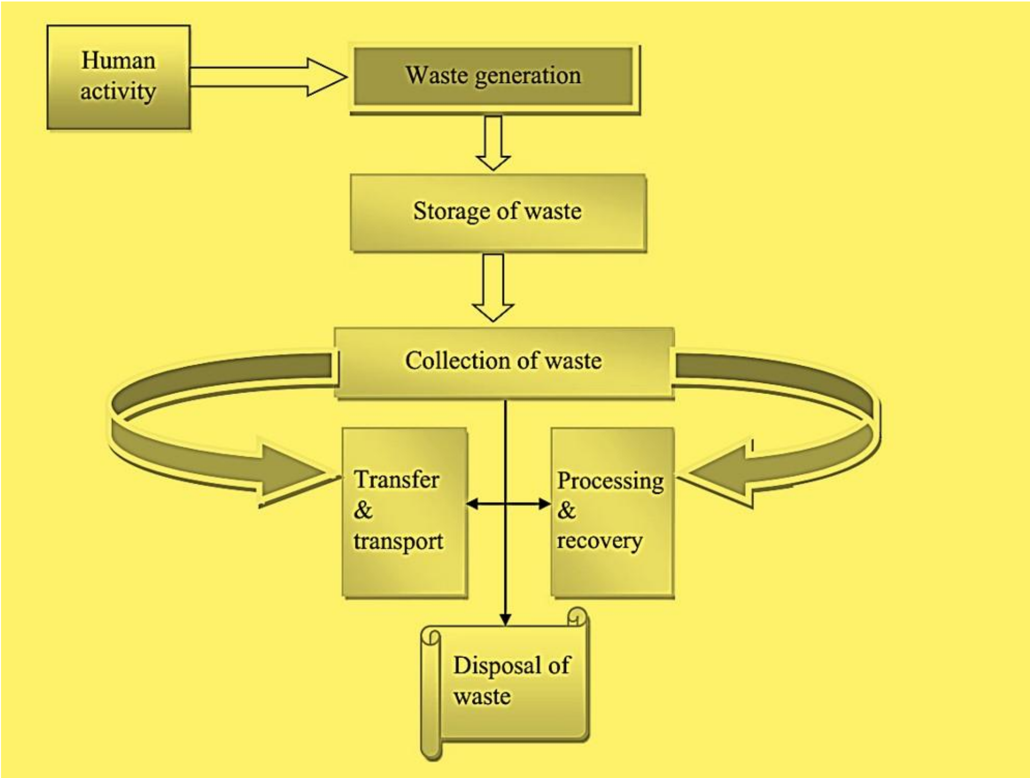

Figure 1. A diagram of the WM framework (Banerjee et al. 2018b).

COMPOSTING

Composting is an aerobic decomposition system that is supported by a diverse microorganism community. By using the metabolic operation of a microbial consortium, this method has been commonly used for various forms of wastes. Composting is a method of transforming and stabilizing organic waste into a more safe and stable form that can be used in several agricultural practices (García-Gómez, Bernal, and Roig 2005). It is a cost-effective and environmentally friendly waste disposal process. Composting provides humus and plant nutrients as well as carbon dioxide, water, and heat as by-products (Gajalakshmi and Abbasi 2008). This process includes a number of microorganisms, including bacteria, actinomycetes, yeasts, and fungi. The mesophilic phase, the thermophilic phase, and the cooling and maturation phase are the three stages of composting. The types of composting organic matter (OM) and the efficiency or effectiveness of the process, as determined by the degree of aeration and agitation, are the two factors that govern the period or length of the composting phases (Table 1).

Table 1. Summary of the studies for various Solid waste as compost feedstocks (Gajalakshmi and Abbasi 2008)

Compost feedstock	Miroorganisms	Impact on the overall composting process
(Common organic wastes), fruit wastes, vegetable wastes, leaves, hay, newspaper, wheat straw and rice husks.	*Bacillus subtilis* and Pseudomonas	Reduction in C/N ratio, NH_4^+ and NO_3^- ion concentrations and increased compost maturity
Municipal solid waste	Mixed culture (Nitrobacter and Thiobacillus, lignin decomposition composite and fungi)	Improved humification degree of the composting products and increased efficiency of the composting process
Agricultural waste composting	Cellulolytic And Deodorising Bacteria *P. Chrysosporium*	Increasing pile temperature, enhancing the substrate utilizability, and changing other physico-chemical factors.
Food waste (FW)	Ligno-cellulolytic Consortium	Lowered extractable-Na (ext-Na)and electrical conductivity (EC) indicating compost maturity
Kitchen-waste	Bacillus thermoamylovorans, Mixed *Bacillus species* (such as *B. Brevis*, *B. Coagulans* and *B. Licheniformis*	Composting process efficiency increased
Organic waste	Cellulolytic thermophilic actinomycetes	Increased content of humic substances and alleviatedCO2emission during composting.
Wheat bran	*Bacillus subtilis* and Chaetomiumthermophilum	Accelerated the degradation of proteinaceous compounds and the formation of complicated humic-like materials, high composting efficiency and degree of humification
Municipal sludge and solid waste	Microbial inoculums originated from sludge and MSW	Increased enzyme activity,composting stability and maturity (C:N ratio, and germination index)
Municipal solid waste compost	*Aspergillus Niger*	C/N decreased and reduction in process time

COMPOSTABILITY FACTORS

Microorganisms

Several microbes are very efficient at oxidizing or decomposing various organic compounds (OC) into simpler and more stable end products (Atalia et al. 2015a).According to the study, some microorganisms colonize a heap of biodegradable solid waste, including mesophilic bacteria, actinomycetes, fungi, and protozoa (Gajalakshmi and Abbasi 2008). These microbes may develop at an ambient temperature of 10 to 45°C and break down degradable components effectively (Cooperband 2000; Hellmann et al. 1997) (Figure 2). The thermophilic process is the efficient composting phase and can last for weeks. Most OMs are degraded during the thermophilic process (Gajalakshmi and Abbasi 2008; H. Meena et al. 2018).

Temperature

Satisfactory composting temperatures have been recorded to be between 52 – 60°C (MacGregor et al. 1981). The optimum temperature during composting rises to 60–70°C, at which point the majority of microbes become inactive. At temperatures below 20°C, the composting process may be paused or greatly slowed. Temperatures above 60°C have also been shown to minimize microbial activity since they cross the thermophilic borderline of microorganisms at that temperature (Gajalakshmi and Abbasi 2008).

pH

The pH value has a big effect on the composting process. Different pH ranges are preferred by different composting microorganisms. For bacterial growth, a pH range of 6.0–7.5 is ideal, while for fungi, a pH range of 5.5–8.0 is ideal (Gajalakshmi and Abbasi 2008). The loss of nitrogen (N) occurs when the pH value reaches 7.5 (Gajalakshmi and Abbasi 2008). A pH of 6.5 to 7.5 is most likely the optimal temperature for a huge array of microbes (Bhardwaj and Datt 1995). Bacterial activity has been documented to be significantly hindered or even inhibited at pH less than 5.0 (Gajalakshmi and Abbasi 2008).

Amount of Humidity

The recommended and optimal moisture content for starting compost is 60–70%. However, at the end of the process, 50–60 percent moisture content is ideal. Microbial activity is substantially reduced by moisture content greater than 75% and less than 30% (Debertoldi, Vallini, and Pera 1983). Moisture content is efficiently regulated by striking a balance between microbial activity and usable oxygen (Gajalakshmi and Abbasi 2008). Anaerobic conditions are produced when there is too much moisture, resulting in undesirable products and a foul odour.

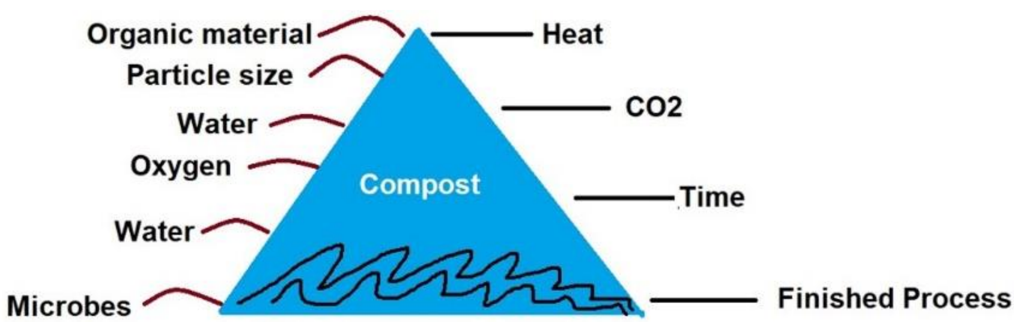

Figure 2. Components of composting represented as pyramid. Redrawn as inspired by the demonstration of Reference (Gajalakshmi and Abbasi 2008; H. Meena et al. 2018).

Carbon and Nitrogen Ratio

Microorganisms need both C and N to survive. C is the primary energy source, and N is required for microbe growth. The C/N ratio, which is initially in the range of 25 to 35, is crucial for rapid and complete humification of a substrate (Gajalakshmi and Abbasi 2008).

Particle Nature and Size

Composting depends heavily on the atmosphere and particle size. The size of the particles has an effect on the amount of oxygen available in the pile as well as microbial ingress into the substrate. Tiny particles increase the amount of surface area available for microbial attack (Atalia et al. 2015b; Sunil Kumar 2018) and larger particles decrease the surface area available for microbial attack, causing the composting machinery to slow down or even stop.

Biodegradation

Biodegradation is an organic way of chemical compound deterioration ("Biodegradation and Bioremediation - 2nd Edition" n.d.).This mechanism is used to degrade organic substances to smaller compounds by living microbial species (Marinescu and Dumitru 2009). WM and environmental abatement are closely linked to biodegradation. Biodegradation in terms of microbiology involves the breakdown of OC, primarily by bacteria, yeast, and fungi from a large variety of microbial flora.

Efficiency for Bacterial Degradation

Several bacteria are capable of degrading hydrocarbons (HC) (Yakimov, Timmis, and Golyshin 2007). Under aerobic and anaerobic conditions, this bacterium can biodegrade HC, but anaerobic biodegradation is more important (Development, n.d.). From the marine environment, a diverse range of bacteria with HC-degrading abilities was isolated. *Bacillus sp.*, *Corynebacterium sp.*, *Staphylococcus sp.*, *Streptococcus sp.*, *Shigella sp.*, and others isolated, efficiently biodegrade HC.

Bacillus sp., *Alcaligenes sp.*, *Acinetobacter sp.*, *Escherichia sp.*, *Klebsiella sp., and Enterobacter sp.* are among the bacteria that may degrade HC. The addition of bacteria has also been documented to degrade pesticides from a variety of compounds, including atrazine (Struthers, Jayachandran, and Moorman 1998). *Bacillus sp.* and *Stenotrophomonas sp.* as well as *Staphylococcus sp.* have been found to degrade dichlorodiphenyltrichloroethane (DDT)(Pergal et al. 2020) from contaminated soil.

Plant-Associated Bacteria Guided Bioremediation

In polluted soil, bacteria associated with plants, such as rhizospheric bacteria and endophytic bacteria, efficiently biodegrades toxic compounds (Divya and Kumar 2018). Rhizobacteria that encourage plant growth can be found in the rhizosphere of plant roots (Saharan 2020). In most cases, the relationship between plant and bacteria is beneficial to the plant because the bacteria aid in nitrogen fixation and nutrient enrichment in the soil (Tank and Saraf 2009; R. Meena et al. 2015). *Pseudomonas sp.*, for example, has a rhizobacteria-like activity that promotes plant growth as well as the ability to degrade HC (Hontzeas et al. 2004). Heavy metal from polluted soil is often efficiently taken up by these bacteria. This bacterium uses a variety of mechanisms for metal absorption, including the synthesis of organic acid and bio-surfactants, which minimize root toxicity and promote plant growth (Wu et al. 2006). Hernce, plant growth-promoting bacteria can improve plant growth in high metal concentrations and serve as a complement in metal phytoremediation (Glick 2010).

Mycorrhizal Degradation Caused by Microfungi

Microfungi are aerobic eukaryotic microorganisms that include mushrooms (Figure 3).

Mycelial moulds to unicellular yeasts. Fungi, like bacteria, have degrading capabilities, and OM in a dissolved condition is successfully digested by them. Fungi may multiply and thrive in low-moisture, low-pH environments, which are ideal for OM decomposition (Juang and Chiou 2007). If fungi are endowed with extracellular multienzyme complexes, they are regarded as the most efficient biodegrading agents of natural polymeric substances.

Several yeasts may use and convert different aromatic chemicals in a co-metabolic manner. Trichosporoncutaneum, a type of soil yeast, has been found to have specific energy-dependent aromatic chemical absorption systems (Mortberg and Neujahr 1985).

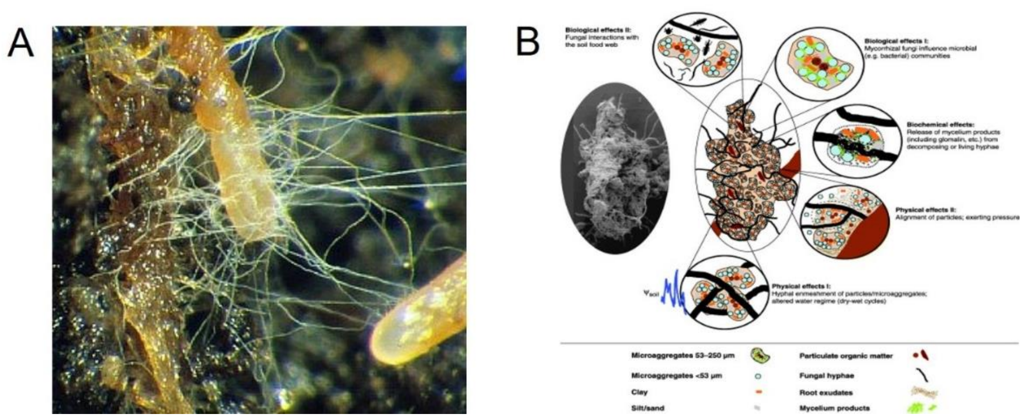

Figure 3. Biodegradation by Mycorrhiza. A. The fungal framework. B. Mycorrhiza and soil structure.

Algal Bio-Decomposition

Although algae can biodegrade various types of HC, their involvement in HC biodegradation is currently under-reported (Das and Chandran 2011). *Prototheca zopfi* is an effective degradant of a variety of aromatic compounds (Walker et al. 1975). Some algae can absorb and degrade PAHs. *Scenedesmus platydiscus, Scenedesmus quadricauda*, *Scenedesmus capricornutum,* and *Chlorella vulgaris* are examples (Wang and Chen 2006).

XENOBIOTIC COMPOUND BIODEGRADATION (XC)

What Does XC Stand for?

Xenobiotic chemicals (Greek xenos = odd, foreign, alien) are chemical compounds created by humans that are not found in nature. They are relatively persistent in the environment because they are very thermodynamically stable. Chemical and pharmaceutical industries, which produce a variety of xenobiotic and synthetic polymers, are the primary sources of XC discharged into the environment. Agriculture and mining modernization produce massive amounts of fertilizers and pesticides, as well as heavy metals, which are released into biogeochemical cycles.

Toxic chlorinated chemicals generated by the pulp and paper industry, as well as large-scale oil spills, exacerbate the situation.

The Effects of XC on the Biosphere

Because xenobiotic chemicals are relatively new to the environment, they are difficult to eliminate. XC are toxic and have negative health consequences, harboring the potential to regulate biological pathways that control development and growth. XC has a negative impact on both smaller and higher eukaryotic organisms ("Utilization Of Fly Ash For Stabilization/Solidification Of Heavy Metal Contaminated Soils" n.d.). The XC's long-lasting and non-degradable nature resulted in bioaccumulation or biomagnification, and it can also be absorbed into food systems (Marchiol et al. 2007).

Biodegradation of Xenobiotics: Mechanisms at Work

Due to its refractory nature, XC is difficult to break down and deteriorate. Different microbes and their enzymes play an important role in the breakdown of such substances. Several studies have found that bacteria, rather than yeast or fungi, are the most important microorganisms for xenobiotic detoxification. Protozoa and microalgae play a minor role in xenobiotic degradation. Among the bacterial group, *Pseudomonas sp.* and *Bacillus sp.* are potent and effective in the breakdown of xenobiotics (Tropel and van der Meer 2004). *Aspergillus niger*, *Gliocladium deliquescens*, and *Penicillium italicum* are among the fungi that can destroy XC (Ekundayo, Olukunle, and Ekundayo, n.d.). Different microorganisms destroy XC in different ways, whether aerobically or anaerobically. Petroleum HC, phenol, naphthalene, benzene, toluene, and other xenobiotic chemicals are swiftly degraded by the aerobic degradation process, whereas chlorinated dioxins are swiftly reduced by the anaerobic degradation process. Pesticides such as DDT and polychlorinated biphenyl (PCB) are among the substances targeted for the anaerobic decomposition process. Genome editing, metabolic engineering to construct functionally competent microbes for xenobiotic degradation have also been other potential approaches in this league for the last few decades. Different methodologies for microbial degradation of xenobiotics have been summarized in Figure 4.

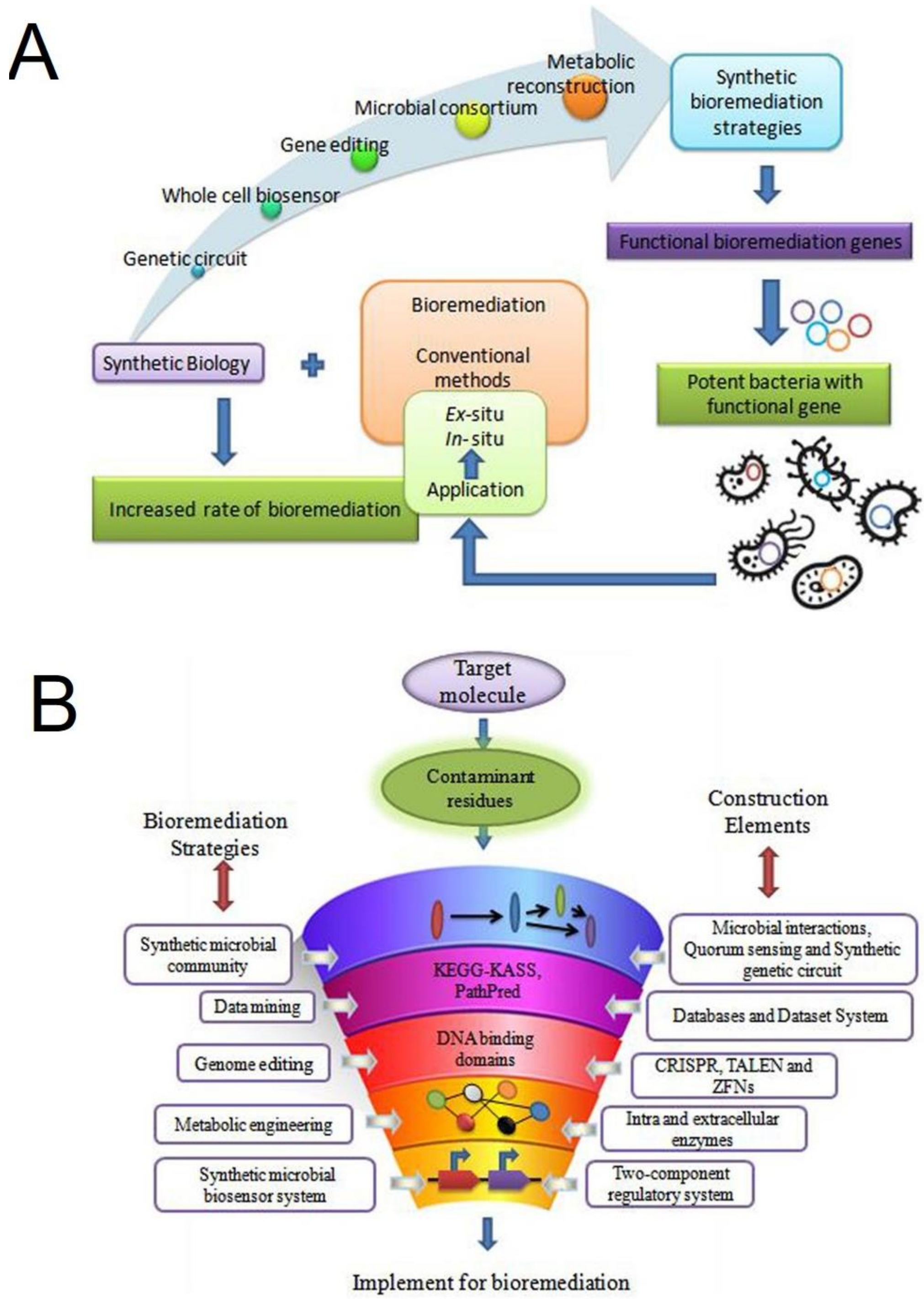

Figure 4. Biodegradation of Xenobiotics A. The general flowchart of methodologies. B. Exploitation of engineering approaches in Microbe. Reprinted with Creative common License permission from Jaiswal, Singh and Shukla @2019.

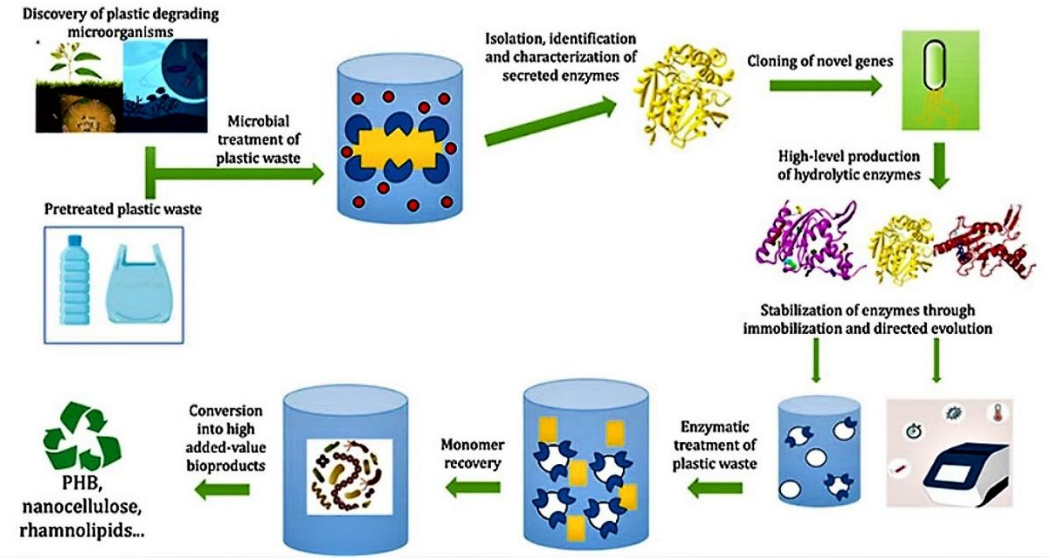

Figure 5. Enzyme engineering (microbial) for solid waste (plastic) degradation. Image published with courtesy from Industrial Biootechnology&Biocatalysis group, School of Chemical Engineering, National Technical University of Athens, Greece. (https://www.chemeng.ntua.gr/indubiocat/biotechnology-in-polymer-science.html, accession date:18-07-2021).

Biodegradation-Involved Microbial Enzymes

The following are the key classes of enzymes that aid in the biodegradation of a wide range of xenobiotics. In downstream processing of solid wastes, usually the enzymes are first over-expressed either native or exogenously, tuned through mutagenesis and directed evolution, immobilized over inert polymeric support by crosslinking or weak covalent bonding, and lastly catalyzing the plastic degradation into recoverable monomers (Figure 5).

Oxidoreductases in Microbes

Oxidoreductases are enzymes that oxidize a variety of pollutants and convert them to innocuous compounds through oxidation-reduction processes (Karigar and Rao 2011). With the help of polymerization and binding to humic compounds, oxidoreductases are a powerful detoxifier of XC belonging to phenolic or anilinic groups (Park, Park, and Kim 2006).

Microbial Oxygenase

These enzymes are members of the oxidoreductase family. Monooxygenases and dioxygenases are the two forms of oxygenases, based on the number of oxygen atoms required for oxidation (Karigar and Rao 2011). Oxidase enzymes are the primary oxidation enzymes in aerobic biodegradation. Oxygenases use flavin adenine dinucleotide, nicotinamide adenine dinucleotide, or nicotinamide adenine dinucleotide phosphate to transport oxygen for the oxidation of substrates as a co-substrate Various OCs are metabolized by the human body oxygenases. These enzymes split the OC's aromatic ring and increase its molecular weight, water solubility and reactivity (Arora 2010). In the bioremediation process, monooxygenases can perform as biocatalysts and have high region selectivity and stereoselectivity on different substrates (Cirino, Biology, and 2002 n.d.; Arora 2010; Banerjee et al. 2018a). Monooxygenases catalyze a variety of processes in aliphatic and aromatic chemicals, including hydroxylation, dehalogenation, desulphurization, biotransformation, and biodegradation (Arora 2010).

Monooxygenases catalyze a variety of processes in the aliphatic and aromatic families, including biotransformation, hydroxylation, de-halogenation, desulphurization, denitrification, ammonification, and biodegradation.

Microbial Dehalogenases

These enzymes are mostly interested in chlorinated contaminants (Cirino, Biology, and 2002 n.d.). Some anaerobic microbes have been shown to utilize halogenated chemicals as electron acceptors and convert perchloroethylene to dichloroethylene, ethylene, or ethane through this method (Wohlfarth and Diekert 1997). Magnuson et al. (1998) used *Dehalococcoides ethenogenes* strain for purification of two reductive dehalogenases (perchloroethylene reductive dehalogenase and trichloroethylene reductive dehalogenase). Perchloroethylene is converted to trichloroethylene by the first enzyme, while trichloroethylene and vinyl chloride are reduced by the second enzyme.

Phosphotriesterases

Phosphotriesterases are a class of hydrolyzing enzyme that specifically cleaves Phosphotriester bonds. These are in general metal depending hydrolases often found with metal activator in their binding sites. Phosphotriesterases are generally used to degrade organophosphate pesticides where phosphotriester and equivalaent bioisosteric bonds are found (Theriot and Grunden 2011).

Biodegradation of Plastic Wastes

Plastics are synthetic polymeric materials that are chemically manufactured and processed for human use, and they are extremely similar to natural resins in many respects. Because of its adaptability, it has made an appearance in many facets of daily life.

Plastics are utilized to make a variety of items because they are resilient, sturdy, light, and inexpensive (Laist 1987). Despite its immense value, it poses significant environmental risks due to its unique properties such as its buoyant nature, ability to disperse over long areas, non biodegradability, and potential for long-term use during many years in the environment (Ryan 1987; Gregory 2009).

Types of Plastics

Plastics are not only stable and long-lasting, but they also have good thermal and mechanical characteristics, resulting in their extensive use in everyday life (Rivard et al. 1995). Monomeric HC is used to make plastics. Plastics are mostly made by chemically altering natural or raw materials, which might be organic or inorganic. Thermoplastics, thermosetting plastics and elastomers are the three kinds of plastics. Based on their physical properties, elastomers and thermoplastics or thermo-softening plastics are used. Based on molecular structure, they can be distinguished in nature. The majority of the thermoplastics are plastics that can be softened and toughened by heating and cooling, chilling to give it shape. Heat cannot be used to modify thermosetting polymers. Rubber-like elastic characteristics are seen in elastomers.

Later, a considerable study was undertaken to determine how to create biodegradable polymers that could be prototyped for microbial assault resistance in an appropriate environment. Biodegradable polymers provide up new avenues for revitalization. Because these polymers are designed to deteriorate under certain conditions, they may be approached using the WM method as environmental circumstances or waste treatment equipment that uses by this biological method (Augusta, Müller, and Widdecke 1992; Witt, Müller, and Deckwer 1997). Due to their resemblance to synthetic plastics, biodegradable plastics have been effectively created for several decades. ThePolyhydroxyalkanoates and polyhydroxybutyrate are the most important biodegradable plastics. Polyhydroxyalkanoates are made from renewable resources and have a long shelf life. In nature, it is biodegradable and biocompatible.

Plastics Have Risks

Plastics are virtually non-biodegradable and are widely discarded after usage. As a result, widespread usage of plastic poses a serious environmental risk to several ecosystems. The buildup of plastic debris has harmed both terrestrial and marine ecosystems substantially. Due to its large production and widespread use, plastic disposal is a serious problem. Plastic pollution has an impact on the marine ecology since it may cause morbidity in many marine species. Many marine creatures, including sea turtles, cetaceans, zooplankton, and sea birds, have been shown to consume plastics that are continually deposited in the aquatic system, according to various studies. When polyvinyl chloride (PVC) is burnt, dioxins are released, which are a powerful carcinogen as well as a disrupter of the immunological and reproductive systems. Bisphenol, a component found in some plastic bottles, has been shown to be a carcinogen and to interfere with the human physiological system. Bisphenol, for example, has been linked to diabetes and early puberty.

Plastic Biodegradation and Role of Microorganism

Plastics are a major source of solid waste. Plastic garbage disposal is a serious issue. Nowadays, there is an issue. Plastic is a polymer, and depending on the nature of the causing agents, it can degrade in a variety of ways, including thermal, photo-oxidative, mechanochemical, catalytic, and biodegradation.

Because of its efficiency and environmental friendliness, the biodegradation process has a lot of promises. The natural ability of microorganisms to initiate degradation is known as biodegradation. Enzymatic activity is used to carry out the process (Albertsson, Andersson, and Karlsson 1987). Microorganisms play an important role in the decomposition and decay of synthetic and natural polymers (Gu 2003). Plastic deterioration is a lengthy process that requires a variety of environmental variables such as temperature and pH. Plastics are mostly degraded by bacteria and fungus. The biodegradation of plastic comprises a number of following stages triggered by enzymatic reactions, the most significant of which is hydrolysis (Heider and Fuchs 1997). Biodegradation of polymeric compounds is regulated by a variety of variables, including the availability of microbial enzymes and the presence of appropriate abiotic conditions. Contaminants are used by microorganisms for growth, nourishment, and reproduction. This is the primary cause for the microbial modification of various organic pollutants. OC provides C to microorganisms. Microorganisms require C because it serves as a building component for new cells. The bacteria also use C as a source of energy (Chapelle 2001).

Microorganism Associated Plastic Degradation

Petroleum-based plastic is considered to be one of the regularly used synthetic polymers that have a wide practice in industries, agriculture, packaging and household matters due to its unique features like pressure resistance, temperature, chemical solvents and UV (Gawande et al. 2012). Recent statistics have also shown that in 2015 the production of plastic has reached up to 388 million tons (Ryberg, Hauschild, and Zwicky 2018). Indiscriminate use and extensive accumulation of plastic wastes in our environment due to their unidirectional use without proper degradation have posed a potent global threat for the environment. Accumulation of such micro-, meso-, or macro debris, within the ecosystem leads to the development of plastic pollution. It has been also observed that improper disposal of plastic wastes like incineration, landfills and recycling results in the development of toxic gases (A. M 1981). The proper disposal of plastics including LDPE can be achieved by the degradation by microbial organisms. This process involves the mechanism of converting the carbon atoms that are present within the plastics to some form, which is relatively harmless for the environment (Figure 6).

Various studies showed that microbial degradation can be considered as an efficient process for disposing of plastics (TA, R, and JR 1995). Macro biological degradation of plastics involves various animals like insects and birds, while the microbial degradation of plastics mainly involves bacteria and fungi for the process of plastic degradation (Pramila and Vijaya Ramesh 2015) (Table 2).

The degradation of polyethylene in association with biofilm results in the degradation of hydrophobilicity (N. M et al. 2021). It has been observed that the utilization of the polyethylene as carbon source by the microbial species helps in the reduction of the dry weight thereby resulting in the degradation of the plastics.

Table 2. Plastic degradation by microbial species

Types of plastics on which they act	**Fungal cells involved**	**Observations**	**Reference**
Low density polyethylene	*Fusariumsolani*, *Aspergillus fumigatus*, *Aspergillus terreus*	*A. fumigatus* and *A. terreus* possess the ability to colonize upon the surface of LDPE and utilizing the carbon source in incubating for a period of 100 days.	(Zahra et al. 2010)
It develops on low crystalline PET films	*Thermomycesinsolens*	It has been observed that 97% of loss in weight of the plastic for incubating at 70°C for a period of 96 hours. The enzyme fungal cutinase is responsible for bringing about the degradation	(Ronkvist et al. 2009)
It develops on low crystalline PET films	*Fusarium solani*	The degradation is mediated by the enzyme cutinase produced by the fungi.	(Ronkvist et al. 2009)
It specifically grows upon the pellets of PET	*Penicillium citrinum*	The enzyme polyesterase from the fungal species is responsible for the degradation of PET	(Liebminger et al. 2009)
It specifically grows upon the pellets of PET	*Penicillium funiculosum*	It helps in bringing about alteration within the polymeric chains as analyzed after 84 days with the help of FT-IR	(Nowak et al., 2011)
It grows upon the LDPE films	*Aspergillus versicolor*	It has been observed the fungal cells are responsible for converting LDPE to carbon dioxide.	(Sindujaa et al. 2011)
It grows upon the surfaces of PVC and PE sheets	*A. versicolor*, *A. niger*, *A. flavus*, *Penicillium sp.*,*M. hiemalis.*, *F. oxysporum*,*F. solani*, *Phoma* sp.*Chrysonilia setophila*	The fungal species were able to bring about the degradation of the plastics in incubating for 2 months analyzed spectroscopically, FT-IR and SEM	(Sakhalkar and Mishra, 2013)
It usually grows upon the surface of PVC films	*A. niger*, *A. sydowii*, *Lentinusti grinus*, *Phanerochaete chrysosporium*	It brings about degradation in colour and the texture of the PVC films	(Ali et al. 2014)
It specifically grows upon the surface of LDPE	*A. niger*in association within the culture of *Lysininacillu sxylanilyticus*	It helps in bringing about the degradation of LDPE at a percent of 29% for UV radiated and 16% for non-UV radiated	(Esmaeili et al. 2013)
It grows on the surface of polyethylene	*A. terreus*and *A. sydowii*	The fungal species can bring about degradation for incubation for 60 days	(Sangale, Shahnawaz, and Ade 2019)
They grow majorly on the surface of PVC	*Chaetomiumglobosum*	The fungal species shows considerable attachment with the surface of PVC thus helping in degradation.	(Vivi et al. 2019)
Grows upon the surfaces of LDPE	*A. oryzae*	Shows marked reduction in the weight of LDPE for incubating 4 months.	(Muhonja et al. 2018)
Grows upon the surfaces of LDPE and HDPE	*P. chrysogenum*and *P. oxalicum*	It degrades PE in incubating for 60 days	(Ojha et al. 2017)
Used Plastic bags from waste (LDPE with black /white tint)	*Alcaligenes faecalis LNDR-19*	Degradation was achieved in 70 days	(Nag et al. 2021)

Types of plastics on which they act	Fungal cells involved	Observations	Reference
LDPE	*Alcanivorax borkumensis*	70 days	(Delacuvellerie et al. 2019)
High-density polyethylene (HDPE)	*Achromobacter xylosoxidans*	150 days	(Kowalczyk et al. 2016)
Polyethylene films	*Rhodococcusruber C208*	30 days	(Orr et al. 2004)
HDPE and LDPE sheets	*Penicillium chrysogenum* NS10	90 days	(Ojha et al. 2017)
HDPE and LDPE sheets	*Penicillium oxalicum NS4*	90 days	(Ojha et al. 2017)

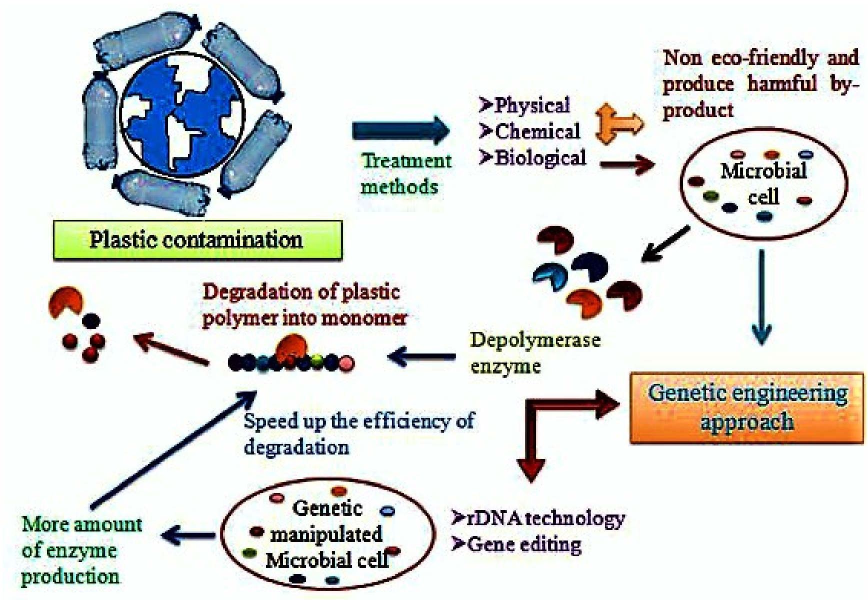

Figure 6. Snapshot of Microbial engineering for plastic degradation. Reprinted with Permission from Jaiswal et al., 2020; copyright @Elsevier 2019.

Microbial Degradation Impacting Factors

The chemical composition and quantity of toxins and pollutants, their accessibility to microorganisms, and, most significantly, environmental variables all influence microorganism efficiency (Kaplan and Kitts 2004). There are two sorts of significant factors that influence the pace of microbial degradation: biological factors and environmental factors.

Microbial Biofilm Mediated Waste Water Treatment

Biofilms may be defined as some aggregated biological structures which are formed on various surfaces that are constantly coming in contact with water. They have complex structures having dynamic characteristics of primeval microbes attached together. Biofilms are composed of prokaryotic cells and cells of other microbes like fungi, protozoa and yeasts (N. M et al. 2021). These microorganisms produce a mucilaginous defensive shield called exopolysaccharide or extra polymeric substance (EPS) on surfaces in which they aggregate.Biofilms provide the microbe's resistance against unfavorable conditions and also help them to survive under stress. In the biofilm system, the microbial cells remain embedded within the EPS matrix and consist of two layers: substratum (on which the biofilm formation occurs) and the bulk phase (phase floating over biofilm). Biofilms have some negative effects such as dental plaque formation leading to tooth decay and gum diseases (Lahiri et al. 2019), food-borne diseases and also algal mat formation causing eutrophication in water bodies. In spite of some of the harmful effects, biofilm formation can be controlled and may be used to treat wastewater (in the present case, industrial wastewater).

Types of reactors that are used for algal- prokaryotic mediated treatment of wastewater are closed photobioreactors, open ponds (waste stabilization ponds (WSP), high rate algal ponds (HRAP) and biofilm/attached growth reactors. Generally, WSPs and HRAPs require less investment cost but system control is not up to the mark. Closed reactors like flat plate or tubular photobioreactors require more investment cost and the conditions for growth can be easily controlled thereby increasing biomass production in a comparatively smaller surface of area (Jasu et al. 2021).

System Biology Approach in Microbial Remediation of Wastes

The mechanism of gene editing involves the process of manipulation of DNA with the help of engineered nucleases. The use of nucleases has proven to have immense application in vast areas of researches including animals, plants and microbes (Butt et al. 2018). Studies have shown that the gene-editing tools possess the ability to enhance the rate of bioremediation by the mechanism of conversion of toxic compounds to lesser toxic substances, elimination of the xenobiotics, remediation of heavy metals and ability to degrade complex forms of the pesticides (Basu 2018). At present condition, the major genome-editing tools such as Zinc Finger Nucleases (ZFN), TALEN and CRISPR-Cas have been proven to enhance the mechanism of bioremediation. The mechanism of CRISPR-Cas is one of the most effective mechanisms for gene editing which comprises of three major types of engineering (Y et al. 2018). TALEN or Transcription Activator Like Effector Nuclease also acts as an efficient tool for gene editing and helps in enhancing the rate of bioremediation (Figure 7).

Another commonly used mechanism of gene-editing is the exploitation of Zinc Finger Nucleases or Zinc Finger Proteins (ZFPs) which helps in accurate target gene editing that could be retrieved from various bioinformatics databases (Table 3).

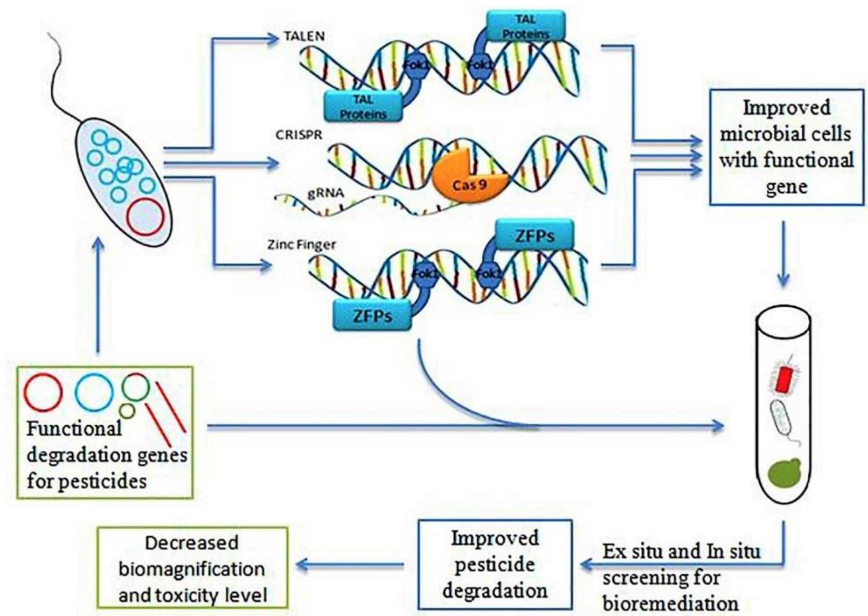

Figure 7. Microbial degradation of solid wastes with genome editing toolbox. Reprinted with Creative common License permission from Jaiswal, Singh and Shukla @2019.

Table 3. Computation oriented biodegradation studies

Databases for understanding Bioremediations	**Links for the servers**	**Utility in the process of Bioremediation**	**Reference**
The Environmental Contaminant Biotransformation Pathway (EAWAGBBD/PPS)	https://envipath.org/	Provides the multi-omics information	(Malla et al. 2018)
Microbial Genome Database (MBGD)	http://mbgd.genome/	Provides information about comparative aspects on microbial genome.	(Fory et al. 2014)
Metarouter	http://pdg.cnb.uam.es/MetaRouter	It helps in maintaining diverse information related to biodegradation or bioremediation	(Paliwal, Puranik, and Purohit 2011)
Metabolic Pathway Database (MetaCyc)	https://metacyc.org/	It helps in assessing the catabolic pathways and helps in predicting various metabolic pathways	(Millacura et al. 2017)

BIOREMEDIATION

Bioremediation is a natural process in which microorganisms are used to eliminate trash or pollutants from water and soil. This is an environmentally friendly and long-term solution since it uses environmentally friendly microorganisms to handle solid waste (Vidali 2001).

There are two types:

In Situ Bioremediation

It is the process of removing pollutants from water or soil without excavating or transporting them. Bacteria carry out biological treatment on the waste's surface. It is an alternate treatment approach for soil and groundwater. Non-toxic microorganisms are used in this approach. There are three forms of bioremediation:

Biosparging

It is a waste management procedure for petroleum products such as diesel, gasoline, and lubricating oil at sites. The concentration of oxygen is raised in this approach by pumping air under pressure into the groundwater. To avoid the escape of gases, air pressure must be properly regulated. The air pollution is caused by the release of volatile particles into the atmosphere.

Bioventing

It's the process through which waste chemicals are aerobically destroyed.

Bioventing is a treatment method for various solid wastes created during the extraction of gasoline and petroleum from oil reservoirs. In this procedure, oxygen and nutrients such as phosphorus and nitrogen are pumped into a polluted location by increasing the removal process's speed.

Bio Enhancement

In this case, cultivated microorganisms are introduced to a contaminated location with the goal of biodegrading pollutants in a particular habitat. This method ensures that pollutants in the groundwater and soil are broken down into non-toxic compounds by microorganisms.

Ex Situ Bioremediation

This term refers to the procedure of removing contaminated soil or water from the environment for treatment. *Ex-situ* bioremediation can be classified into the following categories:

1. Composting: Composting is an aerobic process in which polluted soil is turned into compost coupled with organic amendments that are safe. Organic amendments are beneficial to increase the microbial population in large numbers
2. Land farming: This is a bioremediation technique in which polluted land is cultivated. After mixing the soil with soil amendments, the mixture is tilled into the ground. The major goal is to improve indigenous biodegradative systems by aerobic degradation of pollutants using microorganisms
3. Bio-piling: This is a hybrid method that makes use of bacteria.

Conclusion

Thus, it may be concluded that microbial bioprocesses involving composting, biopiling, bioventing and such others may play a classical role to waste management. However, advancements in systems biology such as genome editing, genetic manipulation have uplifted the efficiency and target specificity of such processes. Since solid waste has grown as a significant burden on society, microbial treatment of such layers has been one notable achievement of the scientific community taking into consideration that such bioprocesses are greener, efficient, sustainable and renewable routes to tackle waste management. The application of enzymatic biocatalysis has been another interesting but efficient approach to manage solid wastes where many solvo-tolerant enzymes have been exploited in such processes. Encompassing all these avenues, it is not overwhelming to assume that more advanced techniques such as directed evolution, nano-biotechnology, nano-biocomposites, bioelectronics,or such hyphenated approaches may be on the way to revolutionize microbial solid waste management.

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About the Editor

Nanda Gopal Sahoo earned his PhD in material science from the Indian Institute of Technology, (IIT) Kharagpur, India in 2004. After pursuing his PhD, he worked in several countries with eminent scientists in a wide spectrum of research fields and gained expertise and scientific orientation in several streams. He held the Scientist position (2012-13) in the Institute of Materials Research and Engineering, A*Star, Singapore. Prior to this, he worked as a scientist with the Energy Research Institute at Nanyang Technological University (NTU) (ERI@N) (2011-2012). In 2008, he was awarded the most prestigious Lee Kuan Yew fellowship (2008-2011) in the School of Mechanical and Aerospace Engineering (MAE), NTU. Prior to the Lee Kuan Yew fellowship, he had the opportunity to work as a Research Fellow at the School of Chemical and Biomedical Engineering, NTU, (2006-2008) and at the Artificial Muscle Research Center, Konkuk University, South Korea (2005-2006).

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