Emerging and Eco-friendly Approaches for Waste Management

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Abstract

The exponential increase in waste accumulation with the increase in population at a global level is posing a great threat to the environment. Along with this, poor management and disposal systems, in turn, increase the adversity. Management of such enormously growing waste is a need for the scenario. Various organic and inorganic contaminants present in the waste possess the potential to harm the environment and need proper treatment before they encounter an environmental niche, to reduce their adverse effects. Conventional physical, chemical and biological treatments though can break these contaminants but are either less efficient or in turn cause damage to the environment due to the utilization of harsh chemicals, temperature or pressure conditions. High-efficiency eco-friendly treatments like enzymatic degradation, bioremediation, phytoremediation and composting can not only reduce the produced waste to a great extent but can also produce valuable products like biofuels, biofertilizers, etc. Henceforth, the present chapter illustrates the conventional as well as emerging eco-friendly approaches which can be utilized at a global scale to minimize the increasing threat of waste accumulation. Moreover, updated researches and waste management trends have been discussed to present an actual status of the eco-friendly approaches in waste management.

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Waste management · Eco-friendly approaches · Enzymatic degradation · Bioremediation · Composting · Phytoremediation

3.1 Introduction

Globally increasing population and industrialization not only upsurge the requirement of resources but also enhances waste production. According to the World Bank report entitled "What a waste 2.0", the global waste is expected to rise to 3.40 billion tonnes by 2050. Currently, the whole world generates approximately 2 billion of solid waste annually, and out of that 33% of waste is not being treated in an eco-friendly and sustainable manner (Kaza et al. 2018). The most probable associated reasons are population growth, rapid urbanization and higher income. Globally enhanced production of different types of waste including household, municipal waste, agricultural waste, industrial waste, etc. adversely affects the environment. The release of unprocessed and incompletely treated waste from industries and municipality has caused a great threat to various life forms. The waste released from various industries like iron and steel processing, mining, distilleries, textile, leather processing, paper milling, etc. produces harmful and toxic pollutants such as sulphides, halides, phenols, heavy metals, polymers, synthetic dyes, pathogens which pose a serious impact on natural resources as well as are responsible for causing severe health hazards (Table 3.1) (Abdel-Shafy and Mansour 2018; Sharma and Bhattacharya 2017). The huge amount of cellulosic waste from agricultural industries and the contaminated water containing pesticides, insecticides and other chemicals, in turn, cause adverse effects on the environment.

Some of the conventional methods of treating waste are incineration, landfill, adsorption, composting, thermal treatment, etc. but due to their high operational cost

Table 3.1 The various health-related and environmental problems caused by toxic waste

Toxic waste	Problem	Reference
Chemicals such as POPs (persistent organic pollutants), phthalates, hydrocarbons	Neurological disorders Endocrine diseases	Zeliger (2013) Bharagava et al. (2020)
Toxic carcinogens such as benzene, vinyl chloride, etc.	Cancer	Uccello et al. (2012)
Presence of particulate matter, gaseous pollutants, etc.	Intensifies asthma	Guarnieri and Balmes (2014)
Lead disposal in open fields and water bodies	Nervous system failure, low IQ, stunted growth, etc.	Wani et al. (2015)
Methylmercury discharged from chemical plants in water	Minamata disease	Rai et al. (2019)
Heavy metal disposal on land	Accumulation of heavy metals in the food chain	Bharadwaj et al. (2015)

Table 3.2 Increasing trends of publications in eco-friendly approaches for waste management from 1990–2000, 2000–2010 and 2010–2020 (Source: Google scholar)

S. No.	Eco-friendly approach for waste treatment	Number of publications in years		
		1990–2000	2000–2010	2010–2020
1.	Biomethanation	628	1600	6670
2.	Bioremediation	13,100	28,400	38,900
3.	Composting	15,800	42,100	54,800
4.	Enzymatic degradation	15,300	30,700	35,200
5.	Phytoremediation	2540	13,200	20,400

and energy requirements, they are less preferred nowadays. Biotechnological approaches like enzymatic degradation, bioremediation, phytoremediation, etc. are highly eco-friendly, low cost and efficient methods which possess great potential to convert waste to valuable products. Conversion of waste to biofuel and biogas by using biological methods is of great interest to scientific society in the current scenario and is being enormously investigated (Ezeonu et al. 2012; Martínez et al. 2015; Berhe and Sahu 2017). Numerous researches have been done till date to develop such eco-friendly approaches and the enormous increase in the number of publications related to these approaches provides great evidence for their viability (Table 3.2). The present chapter provides deep insights of these eco-friendly approaches which are being developed and utilized for waste management along with some conventional methods. Different types of waste, its impact on the environment and its global production trends have also been illustrated to put forward the scope of eco-friendly approaches at a global level to preserve the environment.

3.2 Global Trends in Waste Production and Management

Global waste index 2019 ranked Turkey, New Zealand, Latvia, Chile, Mexico, Italy, Canada, Estonia, Israel and the Slovak Republic among the top 10 waste producers of the world. Though the USA is the biggest waste producer accounting for 808 kg of waste produced by each citizen every year, its efficient waste management and recycling system leads overall reduction of waste and hence it is ranked 12th (https://sensoneo.com/sensoneo-global-waste-index-2019/). Statistical data supports the fact that most of the world's waste is being generated in East Asia and Pacific region followed by Europe and North America (Kaza et al. 2018). The global population has reached 7.6 billion, and the growth in the number of individuals has increased the level of consumption of goods and services, which constitutes the rise in total global waste.

The World Bank has classified economies on the basis of Gross National Income (GNI) per capita data, and facts reveal that higher-income countries are generating over 34% of the global waste.

Waste generation is not the major concern, but the way by which this waste is being processed is of more importance. Unethical management or mismanagement of waste can lead to environmental catastrophe. So, it is the need of the hour to treat waste in an eco-friendly and sustainable manner (https://www.epa.gov/).

In the following sections, we will deal with the types of waste produced around the globe and till date treatments which can be utilized to reduce it.

3.3 Waste Types and Their Effects on the Environment

Waste can be classified into several types based on its origin and the types of contaminants present in it. The major types of waste based on the source of production consist of domestic, industrial, municipal, agricultural, biomedical, radioactive and electronic waste (Velvizhi et al. 2020). Chemical and physical nature of waste plays a major role in its proper disposal and management. The biological aspects of degradability classify the waste into biodegradable and non-biodegradable waste which are of significant concern to develop eco-friendly waste management approaches (Kumar et al. 2017).

A large proportion of domestic and municipal organic waste which consist of vegetable, paper or human waste is being produced all around the world and can be degraded or broken down into simpler non-toxic substance by microbial action when left undisturbed for a long duration. But the plastic waste which is generated around the globe in millions of tonnes poses a great challenge and is classified as non-biodegradable. Polyethylene, polypropylene, polyethylene terephthalate, polystyrene, polyvinyl chloride are the major non-biodegradable forms of plastic used widely in present times. The characteristic features including high molecular weight, hydrophobicity, low number of functional groups which are favourable and crystallinity are highly responsible for the non-biodegradable nature of conventional plastic (Song et al. 2009). Today, variety of biodegradable plastic polymers like polylactic acid, poly-ε-caprolactone, polybutylene succinate, poly(butylene succinate-co-adipate), poly(3-hydroxybutyrateco-3hydroxy-valerate) are being synthesized and some have reached the market as well. They can be possibly degraded by microbial action. However, still, their usage is limited for the majority of purposes as they are unable to meet the desired level of characteristic durability and stress (heat, temperature and pressure) tolerance (Vroman and Tighzert 2009). Thus, the use of conventional non-biodegradable plastic is still highly prevalent, and accumulation of such plastic in environmental niches results in massive damage to environment and living species. Massive accumulation of plastic waste in oceans has grown up into a significant concern as the release of toxic substances into water bodies is causing massive loss of marine life (Hahladakis 2020).

Moreover, a considerable amount of agriculture waste, including cellulosic waste, is generated globally every year. India is ranked 2nd in agriculture-based economies and thus generates a large part of the world's agricultural waste. Burning of cellulosic waste is a common practice in a developing country like India and is a chief reason for excessive air pollution (Saini et al. 2015). The use of physical and chemical treatments utilizes high energy and harsh chemicals, which in turn can cause environmental problems. The biodegradable nature of cellulosic waste provides an advantage, and thus such waste can be treated by composting, but complete degradation of cellulose to more straightforward form requires subjection to good cellulose-degrading microbial flora (Lynd et al. 2002). Further, conversion of cellulosic waste to bioenergy forms by utilization of microbial or enzymatic approaches is a significant concern being exhaustively investigated by scientific society (Robak and Balcerek 2018).

The heavy metal waste from industries and its accumulation causes a significant threat to the environment. Such waste is a common cause of soil and water pollution due to its highly toxic nature. At low concentration, these metals are highly reactive, and when accumulated, they can enter into the food web resulting in serious health hazards to the majority of life forms, including humans. Physical and chemical conventional methods for remediation have been utilized, but low economic feasibility and generation of toxic chemical by-products limit the utilization of these techniques. Biological approaches like bioremediation and phytoremediation utilize microorganisms and plants to absorb and extract heavy metals accumulated in soil and water and have shown promising outcomes in significant recovery of such metal forms in an eco-friendly mode (Barakat 2011; Rai et al. 2019).

Chemical waste from pesticide, food processing and packaging, pharma, petrochemical and textile industries land up in water bodies and soil causing great harm to the environment and variety of living species. Dye production for textile industry accounts for around 800,000 tons every year. Various organic and inorganic chemicals increase the chemical load in environment and accumulation of such huge chemical waste for long can build up highly toxic compounds which can enter into the food chain and cause numerous diseases like renal disorders, central nervous system disorders, etc. Physical and chemical treatment reduces chemical waste from the environment like filtration, adsorption, oxidation, ozonization, etc. are known, but their efficiency and by-products produced in turn pose some limitations. Biodegradation and bioremediation of chemical waste by utilizing microbes or enzymes produced by them have been investigated in many kinds of research and seem to possess great potential in this concern (Randhawa and Kullar 2011; Ali 2010).

However, conventional physical and chemical methods are widely being used, but most of them possess associated limitations and disadvantages. The following sections deal with a brief discussion of physical and chemical and thermo-chemical methods and their associated limitations for waste treatment and management.

3.4 Physical, Chemical and Thermo-chemical Methods of Waste Treatment

Various conventional methods based on physical, chemical and thermo-chemical principles have been developed to reduce a wide range of generated waste (Fig. 3.1). Some methods do possess the potential to convert waste into valuable products,

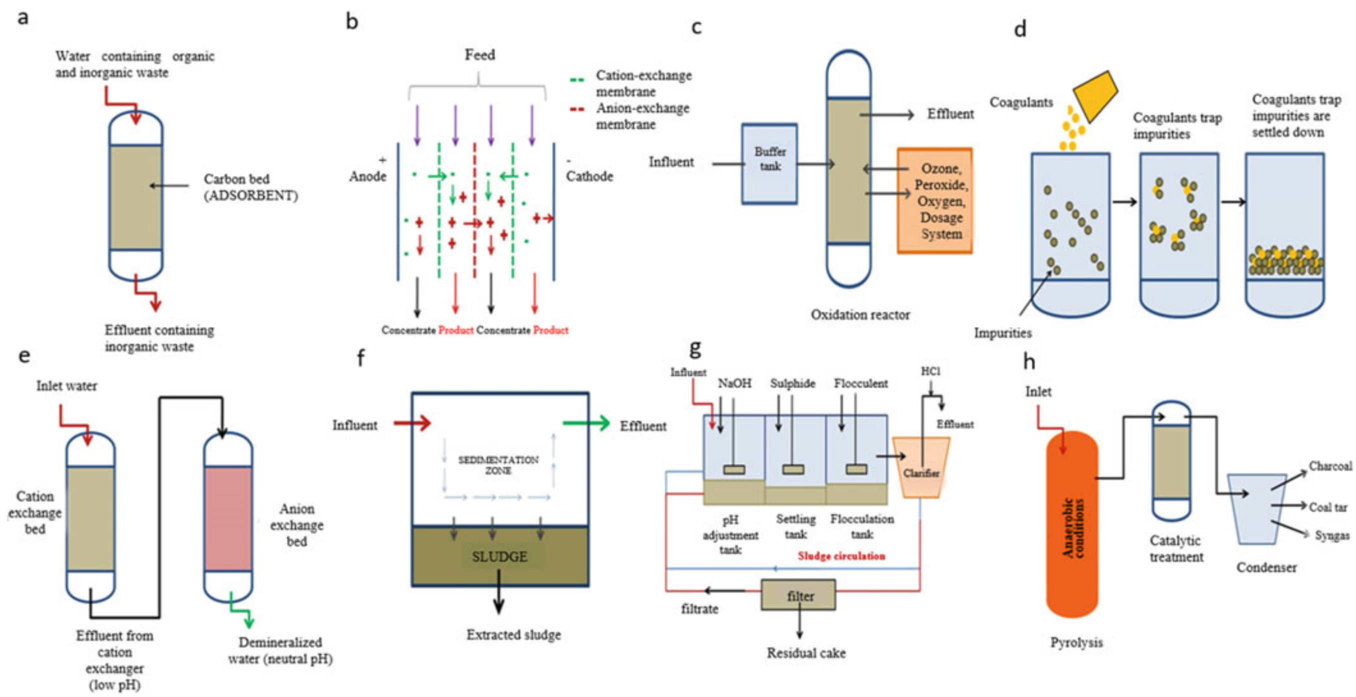

Fig. 3.1 Various physical, chemical and thermo-chemical treatments used for waste treatment: (**a**) Adsorption, (**b**) Electrodialysis, (**c**) Oxidation, (**d**) Coagulation, (**e**) Ion exchange (**f**) Sedimentation, (**g**) Chemical precipitation, (**h**) Pyrolysis

whereas others break the complex compounds into intermediate or simpler ones. The common physical methods utilized for waste treatment consist of adsorption, electrodialysis, ion exchange, sedimentation, photo-catalysis and membrane filtration. Chemical methods which have been utilized to treat waste in large quantities comprised of oxidation, advanced oxidation, coagulation and chemical precipitation. Some thermo-chemical methods include combined heat and power technique, gasification, pyrolysis, incineration, refuse derived fuel pallet formation and catalytic waste conversion (Krounbi et al. 2019; Santos et al. 2020).

3.4.1 Physical Methods

3.4.1.1 Adsorption

Among the various available techniques for the treatment of waste, adsorption is the most efficient process. It involves the use of solid adsorbent and segregates organic waste from inorganic waste. This is a physic-sorption method in which insoluble solid waste can be separated by passing it through an adsorbent which will bind the organic solid waste through a physical or chemical bond (Babel and Kurniawan 2004) as shown in Fig. 3.1a. This method is advantageous over other conventional methods because of its simple designing and low investment for operation. This process is widely being used for the treatment of industrial as well as household waste. The cheapest and readily available adsorbent is activated charcoal (Crini 2005).

3.4.1.2 Electrodialysis

The technique of electrodialysis is mainly used to extract heavy metals from different waste sources, mostly water polluted with heavy metals. Through this technique, ions are separated by passing them through the ion-selective membrane and are concentrated by applying an electric field. With the application of two oppositely charged electrodes on two sides of the membrane, the anions and cations are segregated (Yang and Yang 2006). The membranes are composed of polymers such as styrene or polyethylene, incorporating immobilized and mobile charges (Moreno et al. 2018). The separation is based on the attraction of oppositely charged ions towards the electrodes, and the efficiency of the separation process depends on the pH, flow rate, voltage, water ion concentration, etc. (Mohammadi et al. 2004).

3.4.1.3 Ion Exchange

Ion exchange is an attractive and easy process it employs ionic resins composed of carbon-based structures with attached functional groups. The functional group defines the selectivity of the resin as cationic resin exchange positive charge, whereas anionic resin exchange negative charge (Barakat 2011). The acidic functional groups exchange sodium and hydrogen and form cationic resins while the primary functional groups such as amines exchange hydroxyl ion and form anionic resins. As shown in Fig. 3.1c, the heavy metal ions such as Cr^{+6}, Pb^{+2}, Zn^{+2}, Cu^{+2} and Cd^{+2} can be removed by this technique (Bose et al. 2002).

3.4.1.4 Sedimentation

The heavy waste particles suspended in the slurry waste can be removed by gravitational settling. The waste is blocked into large settling tanks known as clarifiers so that the particles settle down and then can be removed as shown in Fig. 3.1d. The force that drives this clarification process is gravitational force and density gradient difference (Duncan et al. 2018).

3.4.1.5 Photo-Catalysis

Photo-catalysis is a very promising technique that is used for the treatment of waste released from chemical industries. This technique is based on nano-catalysts which absorbs UV radiations from the sun and degrades the toxic pollutants. Pollutants such as organic acids, dyes, pesticides, crude oil, inorganic molecules, etc. are broken down by this energy into simpler substances (Skubal et al. 2002).

3.4.1.6 Membrane Filtration

The waste released from different industries and household contains toxic solids, organic matter and microbes, which can be removed by membrane filtration. This is an advanced filtration technique and employs thin layered semi-permeable membranes. These membranes are composed of organic polymers such as polysulphones, cellulose esters and acetates, polyethene, polyimide/polyamide, polypropylene and polyether ketones, etc. Based on the type of pore size, nature of membrane and charge used for segregation, membrane filtration can be categorized as reverse osmosis, ultrafiltration, nanofiltration and microfiltration (Zhou and Smith 2002). Generally, for the treatment of industrial discharge waste nanofiltration and ultrafiltration are preferred because of high flux, good chemical resistance and pore size. Inorganic contaminants are removed by reverse osmosis where ionic diffusion takes place when the size of the ions of the inorganic contaminants is less than the narrowest part of the pore at low-pressure conditions, and low membrane thickness to porosity ratios (Van Der Bruggen et al. 2003).

3.4.2 Chemical Methods

3.4.2.1 Oxidation

Chemical oxidation of plastic waste along with phenols, chlorides and organic pollutants in large proportion is commonly used chemical treatment to degrade waste (Fig. 3.1e). Fenton's oxidation treatment is very effective in degrading such pollutants. This method works at low pH and degrades organic halides, polyphenols and total organic carbon. The various associated advantages of this method are easy handling and utilization of non-toxic reagents which are safe for the environment (Gogate and Pandit 2004). Advanced oxidation method break down toxic chemicals by the formation of hydroxyl radicals generated during oxidation. This method uses vigorous oxidizing agents like ozone, H_2O_2, catalysts like Fe^{+2}/Fe^{+3}, Mn, TiO_2, $NiSO_4$, CCl, $CuSO_4$ and higher-energy radiations (Dixit et al. 2015; Gogate and Pandit 2004).

3.4.2.2 Coagulation

Coagulation is a primary treatment given to waste slurry to segregate solid waste. In this process, the smaller waste particles present in the slurry are polymerized together to form big particles which are then filtered and subjected to secondary waste degrading treatments (Fig. 3.1f). The coagulants used for this purpose are salts of iron, aluminium, titanium and zirconium (Wan et al. 2019; Lofrano et al. 2013). These coagulating agents are susceptible to pH change.

3.4.2.3 Chemical Precipitation

Chemical precipitation is the method used to separate pollutants such as chlorides, sulphides and heavy metals by using different metallic salts (Mirbagheri and Hosseini 2005). Generally, the metals are precipitated as hydroxides by adding lime, and the other contaminants are removed by adding aluminium sulphate and ferric chloride (Nassef 2012) (Fig. 3.1g). This method is quite economical and also efficient enough to clean large volumes of waste. The major drawback of this method is its pH specificity.

3.4.3 Thermo-Chemical Waste Treatment

3.4.3.1 Combined Heat and Power

Combined heat and power (CHP) technology or cogeneration is used for simultaneous generation of heat and electricity by heat engines or power plants. Cogeneration allows efficient and effective use of primary energy resource (Kalam et al. 2012). It involves the conversion of all primary resources like vegetable oil, coal, biomass, bio-ethanol, heating oil, natural gas, biogas, municipal solid waste, etc. into electricity and heat by using circulation fluidized bed gasification technology. This technology is considered better for fuel conversion than direct combustion. It is highly beneficial for the industries or areas where, along with electricity, heat is also required (Roddy 2012). The deployment of CHP is very cost-effective, requires limited geographic manipulations and is less time-consuming. CHP plants have about 80% efficiency, which is relatively more than the conventional power plants. CHP not only solve the fuel wastage issue, but it also mitigates the harsh climate changes.

3.4.3.2 Pyrolysis

Pyrolysis is a process of decomposing organic waste by application of heat in strict anaerobic condition. As oxygen is absent in this process, no combustion of organic matter occurs, but the matter converts into combustible gases and charcoal. Pyrolysis of biomass gives out the three major products, e.g. bio-oil(liquid), bio-char(solid) and syngas(gas) (Fig. 3.1h). Bio-oil finds its application as low-grade diesel, bio-char increases the fertility of the soil and syngas can be used as fuel or be converted to ethanol by the action of specific enzymes (Devarapalli and Atiyeh 2015). In this process, destruction of the contaminants into smaller particles with lower molecular weight occurs, followed by separation of the contaminants from organic matter. It is highly useful for organic substances like polychlorinated biphenyl (PCBs) and polycyclic aromatic hydrocarbon (PAHs) that are susceptible to cracking at high temperature.

3.4.3.3 Gasification

Gasification is a sustainable process which partially oxidizes carbonaceous matter like coal, pet coke, biomass, etc. into hydrogen, carbon monoxide, carbon dioxide, synthetic fuels, etc. which are collectively called syngas. Syngas is used as a feedstock to chemical industries and can be used to generate power. Waste biomass can be easily converted into energy source by this method with great ease (Farzad et al. 2016). It is a five steps process where firstly the organic matter is dried using high-temperature conditions (100–150 °C). Then, by the process of pyrolysis, the dried mass is converted to charcoal by heating it in the absence of oxygen at 200–500 °C. After charcoal formation, the air is sparged in the gasifier to burn and crack tar into lighter gases at a very high temperature of around 8000–1200 °C. These gases can then be reduced to flammable gases by passing carbon dioxide or water vapour across the bed of red-hot charcoal at 650–900 °C. The residual waste is collected at the landfill, while wastewater is first treated and then discharged into sewage or evaporated in the cooling tower (Breault 2010).

3.4.3.4 Incineration

Incineration is a commonly used process of waste management in which combustion of organic matter takes place. This technology helps in the conversion of waste into ash, flue gas and heat energy. The ash comprises the inorganic matter, and flue gas is released in the atmosphere only after treatment while heat can be utilized in thermal power plant for electricity generation. Though incineration is an exhaustive process, complete decomposition of waste does not occur, and only 80–85% of waste is reduced (Seltenrich 2016). The steps followed in this process include storage of waste and its conversion into feed for incinerator then burning of feed leading to the production of ash and hot gas. The temperature of hot gas is reduced to generate steam, and thus heat energy is recovered. Further, this gas is treated with cold air and then released into the atmosphere. Concludingly, temperature, turbulence and time act as key factors which significantly affect the process efficiency (Kuo et al. 2008).

3.4.3.5 Refuse Derived Fuel Pellet Formation

Refuse derived fuel is composed of combustible waste which cannot be recycled like plastic, label, paper cardboard, etc. This waste is transformed into pellets by compaction of garbage and is rich in organic matter. The moisture and inorganic matter are removed. Because of the reduction in the size of particles, the RDF pellets are homogeneous and are easier to use as compared to municipal solid waste feedstock (Brás et al. 2017).

3.4.3.6 Catalytic Waste Conversion

Waste biomass can sustainably replace fossil fuels for the generation of energy. This strategy includes a reduction in oxygen content of the feedstock for better energy density and formation of C–C bond in the intermediates to increase the molecular weight of the final product. In this process, the waste biomass that is removed in the pyrolysis and gasification process is converted into energy. This whole process is known as aqueous phase reforming. The various catalysts like Pt black, ZrO_2, Al_2O_3, TiO_2, K_2CO_3 convert the biomass into energy. Furthermore, Pd can also be used, but it has less activity as compared to Pt (Park et al. 2012).

Plastic wastes have posed a serious environmental issue. They are non-biodegradable and are synthesized from non-renewable resources. The catalytic cracking of polyethylene and polypropylene can be done quickly by the use of selective catalysts to generate fuel. The various stimuli that are used for this process include Pd, Pt, Rh, Ni. Pd is highly active in this process, but it loses its activity with time-on stream (Keane 2009).

However, various above mentioned physical, chemical and thermo-chemical processes are being used for waste treatment, but the typical limitations of low efficiency, less process versatility, high energy input, harsh working conditions and increased usage of chemicals having toxic effect pose a significant challenge not only to the economy but also to the environment when implemented at large scale. The infrastructures needed for physical treatment methods have low economic feasibility (Garrido-Baserba et al. 2018). The chemical by-products released from chemical treatments of waste too have toxic effects if released in the environment. Complete degradation of conventional plastic is highly problematic even when subjected to high temperature and pressure and low pH conditions thus lead to the release of toxic by-products which have potential to cause significant damage to the environment as well as to associated living being. Chemicals like phthalates and bisphenol A or polychlorinated biphenyls released upon physical and chemical degradation result in highly toxic conditions. Such degradation coverts plastic into particles of microplastic, which spread over long distances and in turn increase pollution (Gallo et al. 2018).

To overcome these challenges, eco-friendly methods are of utmost importance. Microbial or enzymatic treatment of the enormous amount of waste can be a practical approach to deal with the current scenario. Wide variety of microbial genus and species have been investigated in a variety of studies for their ability to treat, reduce and completely biodegrade the hazardous waste. Different microbial flora from various sources has been implemented for the process of waste degradation. Numerous microbial pathways have been revealed which consumes waste components and converts them into valuable products. Scientists have developed leading approaches for treatment and management of waste to value products. The upcoming section discusses in detail the most efficient eco-friendly techniques which can be effectively utilized to treat and manage a considerable amount of waste produced around the globe. Moreover, corresponding researches conducted by numerous research groups have been illustrated to prove the high efficiency of these eco-friendly biological processes (Shalaby 2011; Le et al. 2016).

3.5 Eco-friendly Approaches to Waste Treatments

Though the exponentially growing global waste production is a tremendous challenge to the whole planet, the diverse microbial population present on the earth is compatible with fighting the challenge in a highly productive manner. Enormous biochemical pathway related to the wide range of microbes provides excellent scope to deal with the massive waste produced, with little or no harm to the planet "Earth". The huge piles of biodegradable and non-biodegradable plastic, highly toxic chemicals and heavy metals and lands filled form cellulose waste all can either be reduced to non-toxic forms or into valuable products upon subjection to diverse microbial flora. Activated sludge process, biomethanation, composting, bioremediation and phytoremediation are the leading eco-friendly approaches being implemented and further investigated for treating and reducing loads of waste being generated every year (Fig. 3.2) (Singh et al. 2019; Doiphode et al. 2016).

The conventional activated sludge process is based on the aerobic microbial treatment of solid and organic waste. Leading microorganisms such as bacteria (Bacteroidetes, Acidobacteria, chloroflexi, etc.), algae (Chlorella), fungi (Ascomycetes) are allowed to grow in large aeration tank containing dissolved oxygen and organic waste where they feed on waste and lead to floc formation (Rajasulochana and Preethy 2016). These flocs settle down at the bottom of the tanks and thus can be removed off in later stages (Fig. 3.2a). Though the conventional form of this process was not as efficient, recent developments have linked additional advancement to this process. Guven et al. (2019), in their study on high rated activated sludge process investigated that addition of food waste to municipal waste can further enhance the recovery of energy (Guven et al. 2019).

Biomethanation a multistep process of conversion of organic waste to methane has been well investigated (Fig. 3.2b). Large digester filled with hydrolysed organic waste and microbial flora in anaerobic conditions releases methane (55–75%), carbon dioxide (30–40%), and traces of hydrogen, hydrogen sulphide, ammonia, water vapour and nitrogen (Angelidaki et al. 2011). The two by-products, namely biogas and manure produced by this technology can be directly utilized as biofuel and fertilizer, respectively (Table 3.3). Two stages of biochemical conversions which take place in this process include hydrolysis, acidification and liquefaction at the first stage, and the transformation of acetate, carbon dioxide and hydrogen to methane at the second stage. Mishra et al. (2018) in their biomethanation study of recalcitrant crystalline cellulosic and lignin agricultural waste investigated microbial pretreatments like composting, microaerobic treatment, digestion stage separation and lignocellulolytic fungal treatment to have great potential in increasing methane yield with very low-cost inputs (Mishra et al. 2018). Dahiya and Joseph (2015), designed a high-efficiency biomethanation digester for treatment of food waste giving high biogas yield with around 60% methane content (Dahiya and Joseph 2015). In a recent study, Yang et al. investigated enhanced biofuel production from food waste when syngas biomethanation was integrated with anaerobic digestion of waste and digestate pyrolysis. The production of biomethane increased by 22%

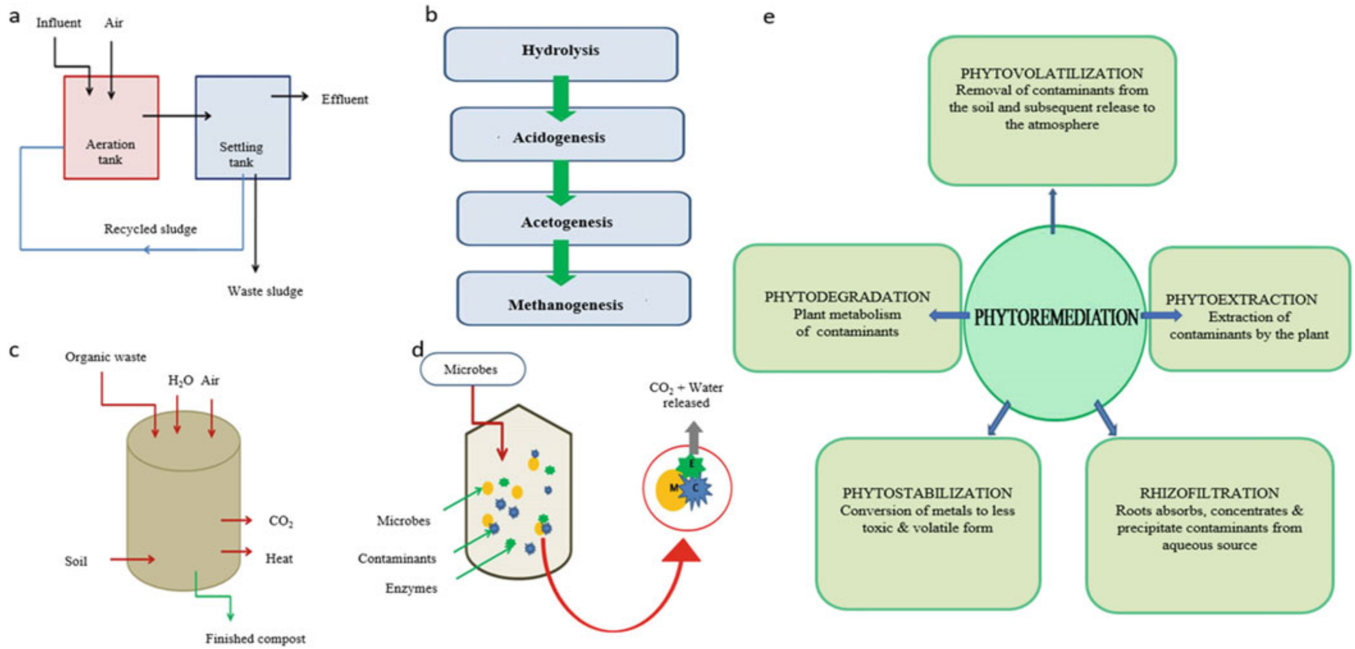

Fig. 3.2 Eco-friendly methods for waste treatment (**a**) Activated sludge process, (**b**) Biomethanation, (**c**) Composting, (**d**) Bioremediation, (**e**) Phytoremediation

Table 3.3 Advantages and disadvantages of biomethanation

Advantages	Disadvantages
It generates gaseous fuel.	The investment is more as compared to landfill and composting.
It can be carried out at a small scale.	The destruction of pathogens in the digesters operating at moderate temperature is less as compared to aerobic composting.
It does not require any external power supply like aerobic composting.	The process is not favourable for waste containing less biodegradable stuff.
The green gases produced in this closed container are collected for use, avoiding emission to the atmosphere.	
For establishing this plant, less land area is required.	
The end products, biogas and manure, are eco-friendly.	

when the gas volume increased from 560 to 5300 ml in heterogenotrophic methanogens containing thermophilic reactors (Yang et al. 2020).

Composting is an effective, eco-friendly, simple biological approach of aerobic degradation of organic waste by microbes (Fig. 3.2c). The compost produced is rich in nutrients which can immensely increase soil fertility, add humus to the soil and act as a natural pesticide as well. It prevents soil erosion by covering landfill areas and land and stream reclamation. The process of decomposition depends on proper air, water, decomposers and physiochemical conditions of temperature and pH. Bacteria and fungi are the main decomposers that produce heat, carbon dioxide and ammonia from the input (Debertoldi et al. 1983). Cellulose present in organic waste is highly recalcitrant in nature and requires specific microbial flora for its digestion. The major bacterial species which poses cellulose-degrading ability are *Cellulomonas*, *Bacillus sp*., *Pseudomonas* and *Thermoactinomycetes,* while the counterpart fungal species are *Trichoderma*, *Aspergillus*, white-rot fungi and *Sclerotium* (Gupta et al. 2012).

Vermicomposting by using earthworms as decomposers is an advancement in composting technology. The vermicast produced by earthworms is known to have high levels of plant nutrients and does not contain pathogenic microbes. Thus, utilization of this technology can not only reduce the waste load but can also provide high-quality manure for cultivation. Pirsaheb et al. (2013) in their vermicompost study on solid waste management depicted high ease of vermicomposting by using a native earthworm species *Eisenia fetida* and suggested vermicomposting can be employed by the homeowner for their produced waste (Pirsaheb et al. 2013).

Enzymatic degradation of solid waste is a highly efficient approach which can be utilized to degrade highly recalcitrant and toxic waste types. Wide range of enzymes can be isolated from microbes and can be immobilized or encapsulated into different substrates or matrices and then can be used for waste degradation. Such immobilization and encapsulation will increase the enzyme efficiency by providing favourable local conditions along with reusability (Feng et al. 2013). The common enzymes employed for this purpose are cellulases, oxidoreductase, ligninase, laccases, peroxidases, tyrosinases, lipases, etc. These enzymes can even degrade resistant polymers like lignin, cellulose as well as phenols and chlorinated and non-chlorinated toxic substances. Alrumman (2016), optimized the process of fermentation and saccharification of cellulosic waste of date palm to lactic acid and glucose by utilizing cellulases produced by *Geobacillus stearothermophilus* and reported effective pH and temperature conditions of 5 and 50 °C, respectively (Alrumman 2016). Another resistant natural polymer present in large proportion in agricultural waste is lignin, which can be effectively degraded by ligninolytic enzymes like lignin peroxidase, laccase, peroxidase and manganese peroxidase (Kumar and Chandra 2020). Past study has reported the effectiveness of above-mentioned lignin-degrading enzymes in the degradation of petroleum-based polyethylene plastic. *Rhodococcus ruber* C2088 strain producing laccase was reported, as an effective strain for degradation of UV irradiated polymer of polyethylene (Gómez-Méndez et al. 2018). Moreover, proteases and esterases have been reported to degrade polyester polyurethane. PET or polyethylene terephthalate is a widely used plastic polymer which was known to be highly resistant to degradation. Several studies have reported significant degradation of PET by bacterial carboxylesterases produced by *B. subtilis, B. licheniformis* and *T. fusca* and cutinase enzyme from *T. insolens* (Wei and Zimmermann 2017).

Bioremediation is a highly effective, economically feasible and eco-friendly technique for degradation of a wide range of waste. This process converts the toxic chemical into simpler non-toxic substances by utilization of different microorganisms. This process consists of three stages, namely biostimulation, bioaugmentation and natural attenuation (Fig. 3.2d) (Jeyasingh and Philip 2005). Commonly used microbes for bioremediation of petroleum-based waste are *Pseudomonas, Bacillus, Alcaligenes, Micrococcus*, etc. Also, the biofilm-forming bacteria provide suitable micro-environment for soil decontamination (Solanki et al. 2020). Hazardous heavy metals which can enter food web and are highly reactive even at low concentration can be effectively absorbed by specific microbial species. These species have high metal holding capacities due to the presence of specific metal sequestrating mechanisms. Zhao et al. (2019) identified four strains, namely CZW2, CZW9, CZW5 and CZW12, which were having high urease activity, from abandoned mine and revealed their high bioremediation efficiency for cadmium removal. These strains remove cadmium by biomineralizing the toxic metal, thus posing no harm to the environment (Zhao et al. 2019). Further, the mechanism of biomineralization of calcium carbonate by various ureolytic bacteria is highly established and is being utilized to reduce high metal loaded toxic waste to a non-toxic form. Bioremediation has also been reported for the treatment of waste from pharmaceutical industries, petrochemical industries, as well as pesticide industries (Dhami et al. 2013). Randhawa and Kullar, in their study on high-efficiency bioremediation approach, using cow dung and its microbiota proved high scope for degradation of toxic chemicals from above-mentioned industries. Another study by Hossain et al. provided strong evidence for textile industry dye wastewater decolourization by white-rot fungi (Randhawa and Kullar 2011). Further, Dussud et al. (2018), while studying biofouling mechanism of marine biofilms over different non-biodegradable and biodegradable plastics, revealed abundant progressive colonization of hydrocarbonoclastic bacteria (Aestuariicella hydrocarbonica, Alcanivorax sp., Marinobacter sp., and Neptuniibacter sp, Lutibacterium anuloederans) over all types of plastics including polyethylene, polyethylene with prooxidant, OXO (artificially aged), polyester and poly 3-hydroxy butyrate co-3-hydroxy-valerate providing evidence for the plastic degrading and colonizing ability of the associated microbes (Dussud et al. 2018). Bryant et al. (2016), in their study on active communities inhabiting on marine plastic debris identified *Bacteroidetes, Cyanobacteria, Alphaproteobacteria* and *Bryozoa* as dominant species inhabiting on plastic debris and seems to be very well adapted to their substrate (Bryant et al. 2016). Oberbeckmann et al. (2016), revealed that Bacteroidetes like *Cryomorphaceae, Flavobacteriaceae, Saprospiraceae* are capable to abundantly colonize non-biodegradable PET plastic bottles. Thus, all these studies depict great scope for bioremediation of plastic by bacterial species capable of degrading the most massive forms of non-biodegradable plastic waste (Oberbeckmann et al. 2016).

Phytoremediation is closely associated with bioremediation and utilizes plants for detoxification of waste and that of the environment. In this technique, the whole plant or specific parts of plants are used to remove pollutants. It is a green technology that converts toxic pollutants into harmless substances (Chaney et al. 1997). Phytoremediation is a combination of five environment-friendly approaches, phytovolatilization, phytodegradation, rhizofiltration, phytoextraction and phytostabilization as described in Fig. 3.2e. It works on the smooth plant–microbe association in rhizospheric region and converts hazardous pollutants to simpler non-toxic ones. Various plants such as *Arabidopsis sp., Thlaspi sp., Sedum alfredii sp.* have great potential in accumulating the toxic components and translocating into other parts of the plant which can be removed off easily (Kavitha et al. 2016). Several researchers have utilized phytoremediation technology for the removal of heavy metals from water and soil (Lone et al. 2008). Liu et al. in their bioremediation study of soil contaminated by petroleum oil suggested ornamental plants of *Fire Phoenix, G. aristata, Fawn, M. sativa* and *E. purpurea* species as highly potent remediators (Liu et al. 2012).

All the above-mentioned eco-friendly approaches provide strong evidence for the high effectiveness of biological treatments for waste treatment, utilization, degradation and reduction. The major advantages associated with these approaches are high economic feasibility, production of valuable by-products, low or null toxic effects on the environment, less space and infrastructure requirement and easily available input materials. Hence, further research to improve these bio-based approaches for large scale waste treatment and enhancement of produced valuable by-products can be of great benefit to society and is urgently demanded.

3.6 Conclusion & Future Prospects

A huge amount of waste is being produced around the earth. The growing urbanization and industrialization have improved the living standard and the choices of the population, which are the significant reasons for the overexploitation of resources and thus enhanced waste production. The increasing waste loads demand for high-efficiency approaches which can be easily practised without any harm to the environment. The conventional physical, chemical and thermo-chemical treatments used for waste management are unable to meet the requirement due to low efficiency and non-environment friendly nature with high associated cost and infrastructure need. Bio-based or biological treatments like composting, bioremediation, enzymatic treatment, biomethanation and phytoremediation are highly eco-friendly and cost-effective approaches and cause very low or null adversity to the environment. Although much research has been conducted to develop these approaches for large scale and for a wide variety of waste produced, further improvement is required to investigate higher efficiency versatile microbes to degrade till date non-biodegradable waste. This chapter provides insights about the conventional as well as recent eco-friendly approaches developed to date for waste treatment to improve awareness and evoke the interest of the readers in this concern.

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