An analysis of technologies in order to move to a sustainable waste management system in the context of Mumbai

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Municipal Solid waste generation has exponentially increased along with worldwide population growth and has caused severe problems including environmental impacts such as air, soil, and water pollution; public health risks such as diseases and respiratory issues; and an economic stress in the form of waste management costs, health care costs, and losses in tourism. Previous technologies to dispose of unsustainable solid waste management including landfilling and open dumping have done more harm to the environment than we can imagine, and it is necessary to implement more sustainable technologies in order to achieve UN SDGs of good health and wellbeing (SDG 3), clean water and sanitation (SDG 6), and primarily sustainable cities and communities (SDG 11). This paper suggests such emerging and sustainable technologies while providing detailed descriptions about the processes involved and evaluations of each technology to give a comprehensive view on solid waste management. It will do so by applying the best suited technology to Mumbai – the financial capital of the most populated country in the world – in order to provide real life applications of these technologies.

Keywords: Technologies; Mumbai; Sustainable; Solid Waste Management

Introduction

In 2012, the World Bank estimated that global waste production per year was 1.3 billion tonnes per year (Kaza et al., 2018). However, in 2016 this number significantly increased to 2.01 billion tonnes and is projected to grow to over 3.40 billion tonnes by 2050 due to population and economic growth. Furthermore, according to the World Bank, in 2016, 1.6 billion tonnes of carbon dioxide equivalent greenhouse gas emissions (COeq) were generated from solid waste treatment/disposal, accounting for 5% of global emissions. These emissions are expected to increase to over 2.38 billion tonnes per year by 2050 if left unchecked (Kaza et al., 2018). Solid waste management (SWM) varies in countries around the world and the technologies used to dispose of municipal solid waste (MSW) are key to creating a more sustainable future. They dictate the consequence of pollution faced by the residents of respective countries and by the entirety of the world. North American countries treat over 54% of the waste by Landfilling and 33% by recycling. In contrast, South Asian countries treat 75% of their waste by dumping in open dumps and only 5% by recycling (Kaza et al., 2018). This stark variation in figures shines an immense light in the disparity faced in Solid Waste Generation worldwide. Moreover, the Great Pacific Garbage Patch (GPGP) is well known to consist of over 1.6 million square kilometres (Lebreton et al., 2018). However, only 1% of all plastic waste which has entered oceans gets trapped in garbage patches (Sebille et al., 2015) and over 90% of the major plastic waste in oceans has originated from Asia (Ravilious, 2017). Hence, it can be seen that the waste treatment in South Asian countries is highly lacking the rigor as seen in North American countries, and Asia is one of the largest waste generators, overwhelming and burdening the ecosystem. India itself has a population of 1.49 billion people and is facing rapid economic change and an increased rate of urbanization, further stressing facilities and producing excess solid waste (R. Chatterjee, 2023). In India, 58.4 million tonnes are generated per year, relative to almost 3% of the total waste generated worldwide (Central Pollution Control Board Delhi, 2021). Due to the overburdened waste disposal, only 12 million tonnes are treated and 31 million tonnes are landfilled (Philipp, 2022). Furthermore, the State of Maharashtra generates the most waste India and accounts for 14% of the total waste (Central Pollution Control Board Delhi, 2021); Mumbai accounts for only 10% of Maharashtra's population but produces over 44% of the state's waste (B. Chatterjee, 2018) – It generates over 11,000 tonnes of MSW per day and less than 10% is segregated and even lesser is treated (Green Communities Foundation, 2019). Therefore, Mumbai will be the focus of this research paper due to the vast amounts of waste being generated and its effects on the environment and population (Section 3).

Methodology

A systematic literature review was conducted in order to find relevant information on solid waste management and sustainable technologies which could be applied to Mumbai, India. This entailed a deep search on the Scopus database by using the keywords: "Solid Waste Management", "Waste Technologies", "Sustainable", "Innovative", and "India". Scopus is Elsevier's database through which reliable and relevant peer-reviewed literature by experts can be accessed. "Solid Waste Management" helped narrow down the search results from all types of waste including medical, industrial, hazardous, agricultural waste, etc. Electronic and plastic waste have been included due to the high percentage of these wastes in the composition of waste in India. Plastic waste composes 8% of waste in South Asia (Figure 2), under which India falls, and electronic waste is on the steady incline in India, projected to increase to 1851337 MT (Figure 9). To analyze "Sustainable" "Waste Technologies" and apply them to Mumbai is the primary aim of this research paper. Hence, it was essential that these keywords were included. "Innovative" helped target newer and advanced technologies which are invented with the thought of being sustainable and can perhaps be applied with further research and development. Currently, landfilling and open dumping are primarily used in India. Therefore, in order to advance and adapt, it is necessary that newer, innovative technologies are applied to India. The focus of the research paper is technologies which can be applied to Mumbai. However, Mumbai would be too narrow and not many quality research studies have been conducted regarding sustainable waste management. Hence, India would provide a broader view and would allow an understanding of current technologies in use, and what the downfalls, in order to improve on the same.

Along with this, literature consisting of books was excluding and a date range from 2016 till 2023 was considered in order to obtain prevalent data. This was followed by an extensive reading of the abstracts of the filtered studies, with the aim of understanding which technology was applied, the maturity of the technology, and if the technology was applied anywhere. Studies which fit the criteria of researching a technology were downloaded and referred to in this literature review paper. The main focus was on finding studies which researched technologies above anything else. A total of 89 papers were found, out of which 47 were downloaded and considered for the research paper. Once done, a detailed spreadsheet was made to ensure a smooth research process, where each paper could be filtered and easily found according to the needs. Data will be presented in data tables, with illustrations presented as figures.

State of Solid Waste Management in Mumbai Today

Maharashtra, the state of Mumbai, is one of the highest urbanized states in India, with over 50% of its population residing in urban areas. According to the Central Pollution Control Board (CPCB), over 22,633 tonnes of solid waste are generated in Maharashtra, constituting 14% of the total solid waste generated in India. Although it has a high collection rate of 99. 79% (Central Pollution Control Board Delhi, 2021), only 32% is treated (B. Chatterjee, 2018). There are 378 composting plants, 89 vermi-composting plants, 47 bio-methanization plants, 18 Refused Derived Fuel (RDF) plants, and 1 Waste to energy plant of 4 MW installed capacity (Central Pollution Control Board Delhi, 2021). The remaining 68% of the waste is disposed of in 161 landfill sites and 237 dumpsites. However, 3 landfills have been capped, nearly 3/5th of the dumpsites have been capped, and none have been converted to sanitary landfills (Central Pollution Control Board Delhi, 2021).

Landfilling is a process which is highly detrimental to the environment and the surrounding population (Danthurebandara et al., 2013). When MSW is decomposed, methane (CH4), carbon dioxide (CO2) and many other components in low concentrations such as ammonia, sulfide, and non-methane volatile organic compounds (VOCs) are produced. Methane and carbon dioxide are potent greenhouse gases, which contribute significantly to global warming, and many of the VOCs are toxic and odorous. Acidic gases contribute to acid rain, which acidifies soil and ecosystems. Strikingly, only 10% of the landfills in India have a gas collection system in place according to a 2018 report by the Ministry of Environment, Forests and Climate Change (MoEF and CC). Furthermore, leachate is formed when any water percolates through the layers of waste in a landfill and picks up soluble and suspended particles of decomposing matter (Vasarhelyi, 2021). The MSW leachate consists of many hazardous, toxic, and carcinogenic chemical contaminants. Mining wastes and sewage sludge contain trace metals such as copper, zinc, cadmium, and lead. These dissolve and travel with the leachate through the landfill polluting groundwater and surface water. Plants take up water containing traces of metals, leading to lower crop growth and productivity (Danthurebandara et al., 2013). It further makes its way up the food chain and threatens animal health. Euotrophication is caused when leachate is mixed with surface water of higher concentrations of nitrate and phosphates and leads to the production of algae and bacteria. This limits the penetration of light into the water and degrades the life of fish species. To quantify this, a study conducted in New York reported that children living within one mile of hazardous landfill sites faced a 12% increase in risk of congenital malformations, and large landfills decrease the value of adjacent land by an average of 12.9% (Vasarhelyi, 2021).

There have been multiple hazards associated with open dumping in Mumbai and the effects due to it are harmful to the environment as well as the residents inhabiting the areas. For instance, In January 2016, a fire broke out at the Deonar dumping ground in Mumbai, India, and resulted in smog in surrounding areas. This continued for almost half a month and released considerable amounts of hexchlorobenzene (HCB), human carcinogen. Long term exposure to HCB can damage developing fetuses, lead to kidney and liver damage and cause fatigue and skin and eye irritation. Deonar is Asia's largest dumping ground with a mind-boggling size of 268 football fields. 9,000 metric tonnes of waste end up here daily without any processing or segregation (Philipp, 2022). Most of the dumps are surrounded by slums and therefore, they are neglected by the government, and fires such as this receive less attention and mitigation. Schools were forced to shut down for 2 days due to the fire at the Deonar dumping ground, and these fires have heavily impacted Mumbai's citizens (Kapur, 2016). Furthermore, the PM2.5 levels increased to 250 $\frac{\mu g}{m^3}$, 10 times the standard level of 25 $\frac{\mu g}{m}$ (S. K. Singh et al., 2021). These dire conditions have caused the life expectancy of residents near Deonar to drop to 40 years compared to the average urban life expectancy of 74 years along with high rates of malnutrition and tuberculosis among residents (Philipp, 2022).

Mumbai had a budget of roughly 10479.3 million rupees for waste management in 2007-2008 (Archana Shirke, 2009). However, much of it did not get spent entirely on waste management. Resource crunches and inefficient infrastructure resulted in wastage of budget and all of the waste did not get transported to the final dumpsites. Due to this, a large part of municipal solid waste (MSW) remained untouched in the collection facilities and continued to grow in size daily. While government statistics show that 66.52% of the waste is treated, in reality, much of this is possibly lying unattended due to the insufficient infrastructure. Moreover, solid waste management (SWM) requires a ready supply of skilled labor, who would be able to handle the process with expertise and care. Knowledge about the proper procedure, use and maintenance of the equipment, health hazards, hygienic handling of the waste is often required when dealing with waste of such great magnitude (Archana Shirke, 2009; Kumar et al., 2017). Therefore, lack of education and training of employees, as in Mumbai, results in a handicapped SWM system. These problems lie at the heart of SWM in Maharashtra and Mumbai and need to be resolved in order to further develop the system.

Emerging Technological Solutions for SWM

This section focuses on the technologies which could lead to a sustainable SWM system in Mumbai. The technologies have been sorted based on the type of waste they dispose of (Figure 1), with a major emphasis on technologies used to dispose of organic waste, as it consists of 57% of all solid waste generated in India (Kaza et al., 2018). Technologies to dispose of e-waste and plastic waste have further been explained. Plastic waste accounts for 8% of the solid waste generated in India and is the third highest proponent of solid waste in India. Per capita plastic consumption was 15 kg per person in India in 2021, reaching a total plastic consumption of 21 million tons in India alone (Statista, 2023). Electronic waste has also skyrocketed in recent years, projected to reach 1851337 MT in 2025. Hence it was essential that these types of waste were emphasized, and technologies were analyzed to curb their impacts on the environment and cities.

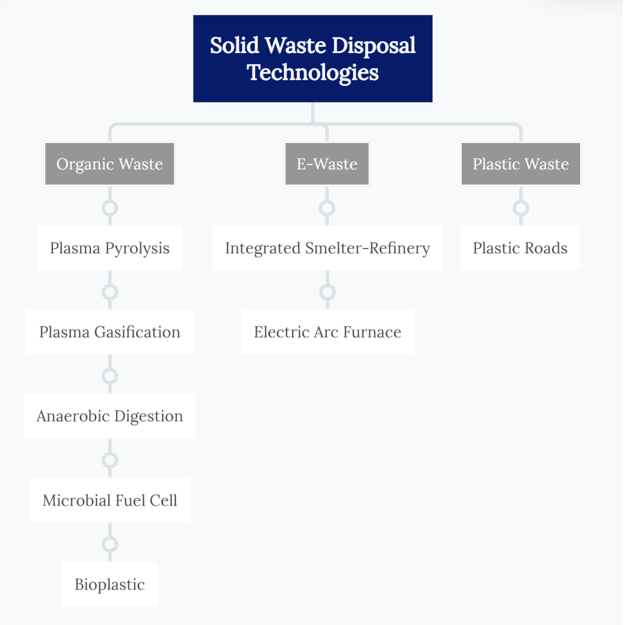

Fig. 1 Solid waste disposal technologies.

Organic Waste

Organic waste is any waste which is biodegradable and comes from the origin of plants or animals. It can be broken down into carbon dioxide, methane, and simple organic molecules. Organic waste includes food waste, agricultural waste, manure, sewage sludge, and paper wood waste (City of Signal Hill, 2017; Patel et al., 2021, p. 10; Twagirayezu et al., 2023, p. 10). More than half of South Asian waste is organic (Figure 2), and hence there need to be proper methods to dispose of this waste (Kaza et al., 2018). The technologies of plasma pyrolysis, plasma gasification, anaerobic digestion, microbial fuel cells, and bioplastics are described to dispose of organic waste.

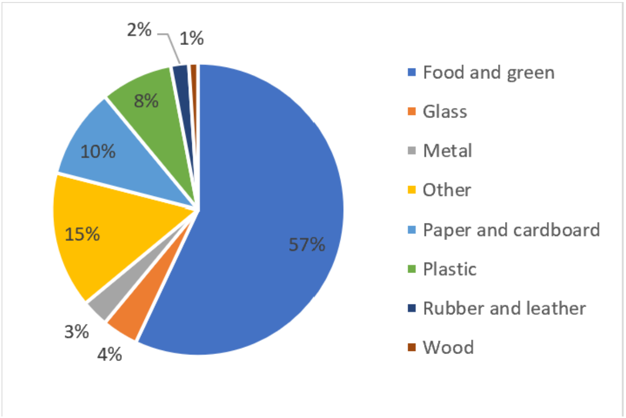

Fig. 2 Composition of waste in South Asia (Kaza et al., 2018)

Plasma Pyrolysis Plasma Pyrolysis is defined as the disintegration of organic compounds into gasses and non-leachable solid residues in an oxygen starved environment according to the Central Pollution Control Board (CPCB) India. It uses electrons, ions, and excited molecules with high energy radiation to decompose chemicals. This versatile process can be used for all types of waste, such as polymer, organic, medical, and hazardous wastes safely (Central Pollution Control Board, 2016). It is a highly efficient process as the graphite electrodes used to produce heat, convert electrical energy into heat energy with over 90% efficiency (Institute for Plasma Research, 2020).

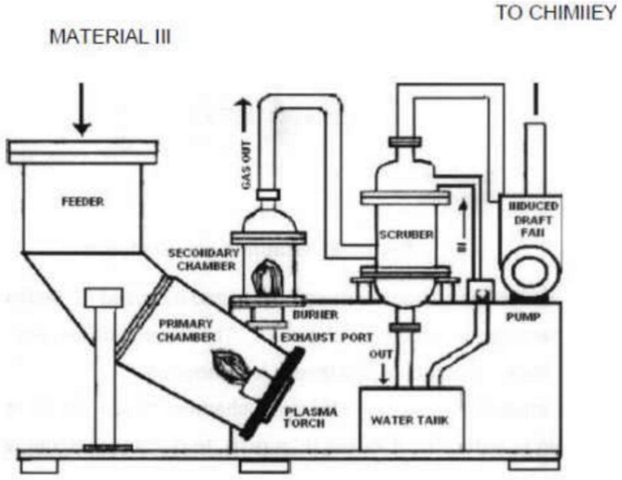

Fig. 3 Flow diagram of Plasma Pyrolysis (Central Pollution Control Board, 2016)

A typical plasma pyrolysis system has the following components (Figure 3):

i Feeder: Used to feed waste material into the primary chamber.

ii Primary Chamber: Designed to reduce heat loss with a refractory lining. It is an oxygen starved environment with temperatures above 1000°C and gases including methane, carbon monoxide, and hydrogen are produced.

iii Plasma Torch and Power Supply: There are 3 electrodes (2 rod shaped cathodes, 1 tubular anode) in the graphite plasma torch. DC power is supplied by a plasma arc at the plasma torch. The electrodes are rotated in an angular motion and are perpendicularly mounted. The torch is used to heat the primary chamber and produce the non-transfer arc.

iv Secondary Chamber: Air is mixed, and an electrically powered igniter ignites the combustible gases out of the primary chamber.

v Scrubbers: Venturi and secondary scrubbers quench and scrub the gases.

vi Induced Fan Draft: Gases are released and treated after going through this.

Table 1 Table 1 Specifications for Plasma Pyrolysis System (Institute for Plasma Research, 2020)

Sr.	Items	Specification
1.	Capacity	15-50 kg/hr
2.	Power Requirement	30kW – 75 kW
3.	Space Required	60 – 200 Sq. Meter
4.	Manpower required to operate plant	2 ITI Persons + 1 Helper
5.	Waste requirement	2000 L/week
6.	Consumables	Graphite electrodes

This technology can be used to safely dispose of biomedical waste, which has been on the rise due to COVID-19; metallized plastics; polyethene plastics; organic waste; and chemical waste. It can solve the problems of disposing of non-recyclable, low grade, and chlorinated plastics, and since it is performed in an oxygen starved environment it does not pollute the environment. Furthermore, it has been approved by the CPCB and the MoEF and CC, and has been included Gazette of India 28th March 2016 (Institute for Plasma Research, 2020). Hence, it complies with environmental regulations. All of the technology can readily be made in India, which can reduce its costs (Table 1). However, it requires a large energy input; the corrosive plasma may cause the need for frequent maintenance and component replacement, resulting in a larger downtime; and it ultimately releases carbon dioxide into the atmosphere (Central Pollution Control

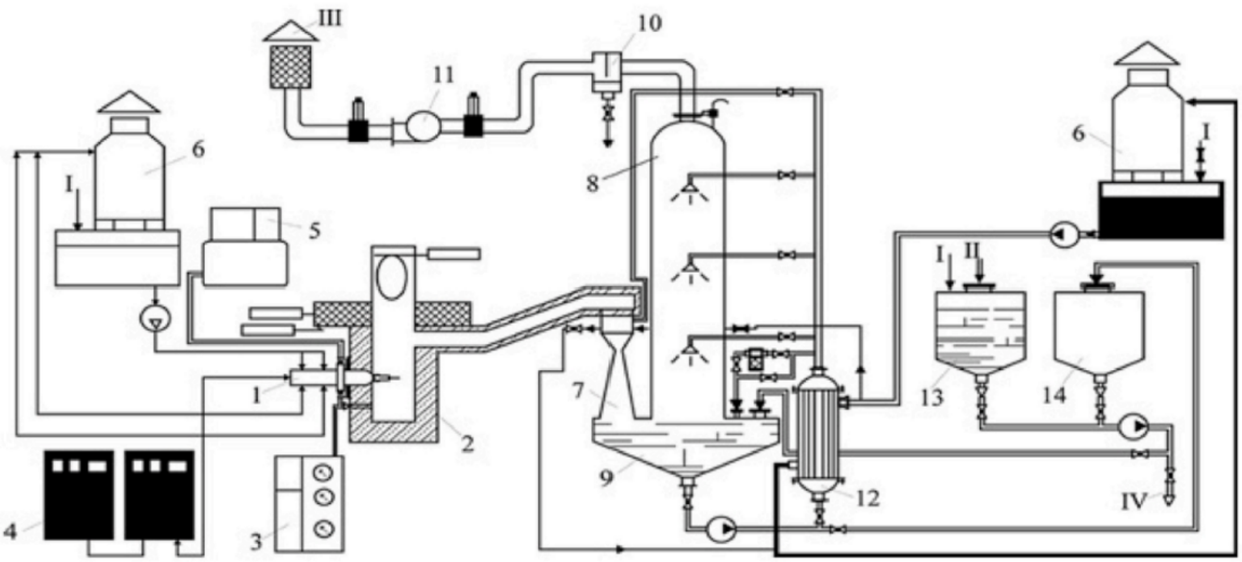

Fig. 4 Schematic diagram of a Plasma Steam Gasification process: 1: plasma torch, 2: plasma steam reactor, 3: steam generator, 4:sequentially connected power sources plasma-2, 5: compressor, 6: cooling tower, 7: Venturi scrubber, 8: system for the gas quenching, 9: under-scrubber capacity, 10: drip pan filter, 11: fan (smoke exhauster), 12: heat exchanger, 13: soda solution tank, 14: sludge tank, I: water supply, II: soda, III: synthesis gas, IV: for utilization (Seyedeh Anahita Mousavi et al., 2021; Zhovtyansky et al., 2013).

Board, 2016). It is important to look at this high energy demand through Mumbai's perspective. There have been several power cuts in Mumbai in June 2023, May 2023, and April 2022 to name a few. These have all been attributed to a rise in the demand for electricity, overburdening the capacity. Moreover, due to shifts to solar energy, the probability of blackouts occurring at night has drastically increased. The rising electricity demand has not been met with subsequent increments in coal-fired or hydropower plants (Mukhopadhyay, 2023; Rao, 2023). Hence, plasma pyrolysis could be straining Mumbai's ability to supply electricity to its growing population.

Plasma Gasification In Plasma Gasification, feedstock is gasified in plasma by a high-energy electricity arc (Figure 4). The process gas is heated to up to 5000°C by a passing of the inert gas through the arc (Evans & Smith, 2012). The plasma torch generates intense heat, removing all the toxins and hazards from the waste. The organic waste deposited is then converted into a synthesis gas (syngas) and the inorganic waste is converted into slag. The syngas contains high amounts of carbon monoxide and hydrogen, which can be converted into electricity by fuel cells and reciprocating engines. Plasma Gasification is done in the presence of oxygen, unlike Plasma Pyrolysis (Seyedeh Anahita Mousavi et al., 2021).

Plasma torches can be adjusted, so plasma gasification is highly flexible with feedstock size, composition, and moisture content. Thus, any type of material can be broken down and converted into syngas, even heterogeneous materials which would otherwise be hard to break down (Evans & Smith, 2012). It has a high efficiency and converts 99% of organic material to syngas (Plasma Gasification, 2010). Moreover, the high temperatures guarantee that no tars and furans are produced, with the trace contaminants in the gas being lower than others. Emissions comply with regulations and meet CPCB norms, without much production of carbon dioxide. It is also highly cost effective and the slag produced can be used to make roads, bricks, and pavements (Plasma Gasification – MEPL, 2019). However, energy requirements may be high in order to power the plasma torches and chlorine levels could be high in the product gas, leading to impurities such as dioxins and metals (Evans & Smith, 2012). Mumbai's already stretched electricity supply would be under major pressure if plasma gasification was used. As mentioned in section 4.1.1, Mumbai has witnessed several power cuts due to an increase in demand for electricity and the switch to plasma gasification will place tremendous stress on the electricity supply.

Anaerobic Digestion Anaerobic Digestion (AD) occurs when bacteria break down organic matter in the absence of oxygen (US EPA, 2019). Biogas can be produced from various inputs such as food waste, cereals, fruit waste, grass, municipal sludge, manure, and straw (Siti Aminah Mohd Johari et al., 2021). This process takes place in a sealed vessel and a reactor, and it is designed and constructed in different shapes and sizes according to the feedstock conditions. The microbial bacteria digest the organic waste into both biogas and a diges-

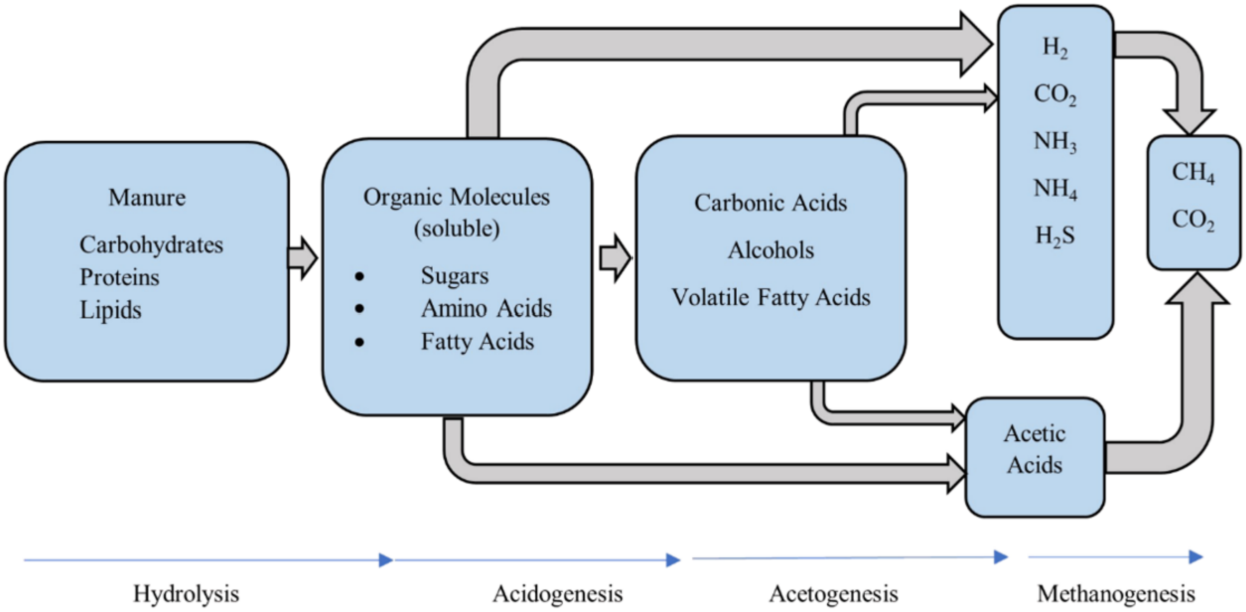

Fig. 5 Four major steps for anaerobic digestion pathway (Siti Aminah Mohd Johari et al., 2021)

tate, which is discharged from the digester (Sunita Varjani et al., 2021).

A typical AD process follows four major steps (Figures 5 and 6):

i Hydrolysis: Complex branched-chain substrates are hydrolysed into their monomers with the help of hydrolytic enzymes and water. Long chain polysaccharides are broken down into simple glucose by the activity of xylanase and amylase. Protein is broken down into amino acids by protease, and lipids are broken down into glycerol by fatty acids. Hydrolysis is enhanced by pre-treating the substrates.

ii Acidogenesis: The hydrolysed product from i) gets converted into hydrogen, acetate, carbon dioxide, organic acids, and others by acidogenic bacteria. This is the fastest step in the process; however, more organic matter is left to be used for methane yield.

iii Acetogenesis: Acetogens digest acidogenic products from ii) into acetic acid, carbon dioxide, and hydrogen.

iv Methanogenesis: Methane, carbon dioxide, and water are produced when methanogens digest the products formed in the previous steps. The rate of the reaction is the fastest between a pH of 6 and a pH of 8. The unreacted organic products form the effluent – digestate (Sunita Varjani et al., 2021).

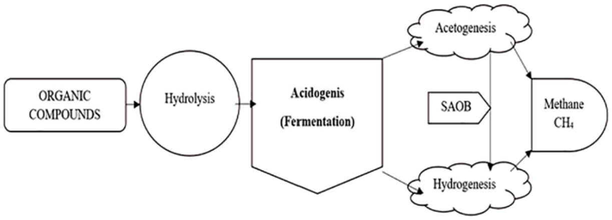

Fig. 6 Biomethane formation summary from an anaerobic process. SAOB stands for Syn-trophic acetic oxidizing bacteria. (Siti Aminah Mohd Johari et al., 2021)

AD can either be performed in a one or two stage system, where Hydrolysis, Acidogenesis, Acetogenesis occur in the first reactor and Methanogenesis occurs in the second reactor. Discontinuous, semi-continuous, and continuous reactors can be used depending on the flow rates. The AD process depends on the type of waste – solid or liquid. When the amount of solid is lower than 15%, it is considered as wet digestion and when it is higher than 15% it is considered as dry digestion (Sunita Varjani et al., 2021). Many microorganisms are involved in the process of anaerobic digestion, and each thrive in conditions dictated by pH, temperature, substrates, hydraulic reaction time (HRT), Carbon to Nitrogen ratio and mixing rate. The pH of substrates influences the growth of methanogens, in the fourth stage where biogas is produced. The optimum pH is at pH 7-8. Different bacteria work efficiently at different temperatures and there is not one temperature range which is optimum for all. For example, thermophiles work best at 50-60 °C, mesophiles work best at 22-40 °C, cryophiles work best at 12-24 °C, and the activity of methanogens can be enhanced by 10 times if the temperature is increased from 10 to 250 °C. HRT is the residence time required by the volume of a liquid substrate, passing through a bioreactor to complete the digestion process. It differs with the type of substrates, composition of substrates, and temperature. The optimum C/N ratio for an anaerobic digester is thought to be 25:30. High C/N ratios cause nitrogen to be used instead of carbon by methanogens, bringing a lower biogas yield. Low C/N ratios are harmful and result in smelling salts and unpredictable unsaturated fats, restraining the creation of biogas (Siti Aminah Mohd Johari et al., 2021; Sunita Varjani et al., 2021). Biogas can be used to provide heat, generate electricity, power cooling systems, etc., acting as an alternative fuel. This can be used to power anaerobic digestion plants, further cutting down the costs of power, and can supply electricity to other places as well, decreasing demand of conventional fuel sources. Therefore, it not only provides an alternative fuel source instead of fossil fuels, but it also decomposes organic waste, combating two problems at once. Furthermore, the digestate produced, when treated, can be used as a nutrient rich fertilizer, foundation material for bio-based products such as bioplastics, organic rich compost, soil amendment, and animal bedding. It is unlikely to cause environmental pollution once used on land as compared to untreated organic waste and the effect of the fertilizer is longer lasting than for untreated organic waste (Last, 2021). Hence, it serves more functions compared to composting and vermi-composting and is a viable technology for disposal of organic waste (US EPA, 2019). However, it requires specific temperature conditions which prove costly to maintain and the digestate contains ammonia, so it needs further treatment before use on land (Last, 2021).

Microbial Fuel Cells Microbial fuel cells (MFCs) are defined as bioreactors that convert the energy contained in the chemical bonds of organic compounds into electrical energy through the catalytic activity of microorganisms under anaerobic conditions. Figure 7 illustrates a typical MFC consisting of 2 chambers – a cathode and an anode chamber – separated by a selectively permeable membrane (Vishwanathan, 2021). In these chambers, six sub-processes develop:

i Substrate breakdown: First, the organic matter is introduced into the anode of the MFC, and the microbes catalyse reactions which lead to the electrochemical oxidation of organic material, releasing electrons.

ii Electron transfer: Electrons released by oxidation are transferred to the anode and create a flow of electrons.

iii Electron transport: The electrons travel through electron transport chains before being donated to the anode. They generate a current in the external circuit as a result.

iv Reduction: Typically, oxygen gets reduced at the cathode and forms water by accepting electrons.

v Proton transfer: The protons get transferred to oxygen as it gets reduced and creates a gradient which drives protons over the membrane to the anode.

vi Electron and proton recombination: At the anode, electrons and protons combine with the microbes to form water and other products.

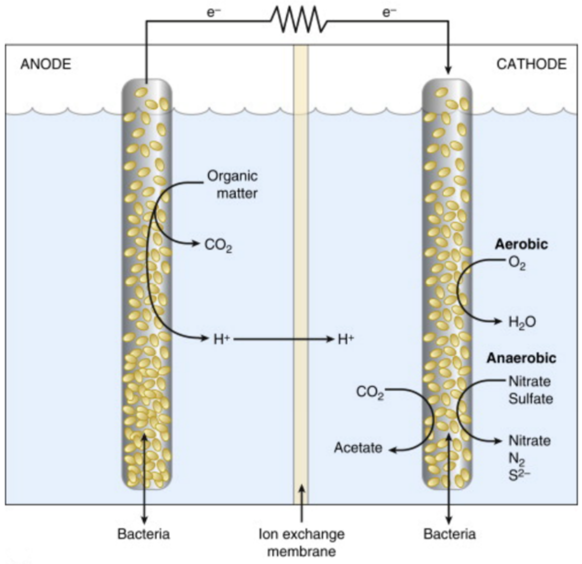

Fig. 7 Diagram of Microbial Fuel Cell (Clark & Pazdernik, 2016)

Carbon is usually used in the anodes because of its non-reactivity, high electrical conductivity, and biocompatibility. The anode must be made out of platinum if oxygen is used as the terminal electron acceptor. Oxygen is typically favoured because of its ubiquity and propensity to get reduced to water. The permeable membrane allows charges to pass through but does not allow direct electrical contact between the anode and the cathode. Several steps can be taken to improve the efficiency of this process. Carbon anodes could be replaced with graphite brush anodes to increase the surface area for reaction. Focusing on the ionic strength and pH on MFC can improve the rate of reactions. Microorganisms operate at different pH levels, and it is important to provide the optimum pH for maximal reaction. Furthermore, co-addition of various inoculums can significantly reduce the startup time for electricity production using MFCs. MFCs are versatile and can treat wastewater

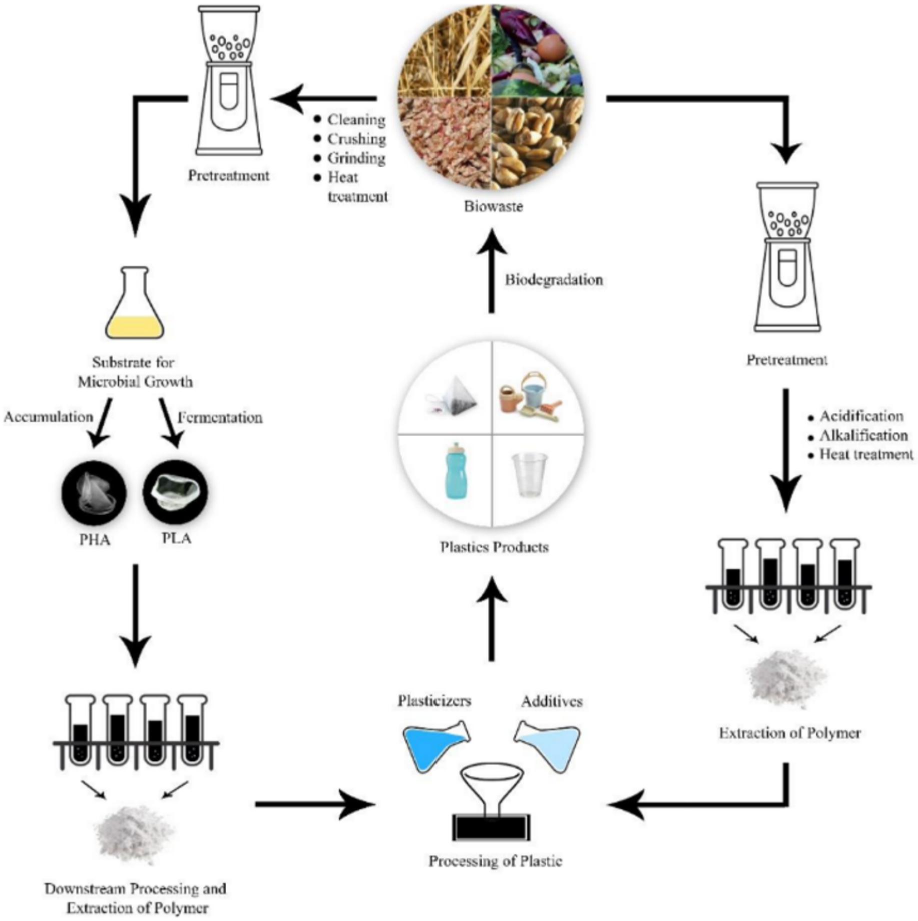

Fig. 8 Generalized Process of Bioplastics Production from Biological Wastes (George et al., 2021)

as well. However, MFCs are still in the research and development phase and require significant development to be used as a reliable method of disposal of organic waste(Anita Talan et al., 2020; Vishwanathan, 2021).

Bioplastics

Bioplastics are polymers that are manufactured from natural or renewable sources (Rudin & Choi, 2013). Bioplastics are an alternative to conventional plastics and their applications. In 2021, the market share of bioplastics was 1% of the 370 million tonnes of total plastic waste produced globally. This is projected to increase to 30% of the total plastic by 2025 (Coppola et al., 2021). However, not all bioplastics are biodegradable. For example, synthetic polymers, polypropylene (PP), polyethylene terephthalate (PET), and polytrimethylene terephthalate are non-biodegradable. On the other hand, Polyhydroxyalkanoate (PHA) and polylactide (PLA) are biodegradable (Coppola et al., 2021).

The method of manufacturing bioplastics depends on the type of material used; however, a generalized process of pretreatment, extraction, and characterization is used, (Figure 8). Detailed methods of formation of bioplastics from sludge waste, cassava peels, banana peels, pineapple peels, durian seeds, avocado seeds and chicken feathers are described in (Ramadhan & Handayani, 2020). See Table 3 for types of bioplastics produced from different wastes. Global plastic consumption has quadrupled over the past 30 years according to the OECD. Plastic production doubled in between 2000 and 2019 to over 460 million tonnes (OECD, 2022b), with almost half meant for single use. Plastic bags themselves take up to 1,000 years to completely disintegrate (Staff, 2022). On the other hand, bioplastics take only 3 to 6 months to decompose fully, and they are wholly made out of organic waste (Serle, 2011). For example, PLA is only derived from corn sugar, potatoes, and sugar cane. In fact, bioplastics have similar degradation rates to paper (Table 2). At the end of their life, bioplastics can be recycled, reprocessed, incinerated or they can be composted and anaerobically digested. Composting in general is the most beneficial and makes the full use of its properties (Coppola et al., 2021). Furthermore, conventional plastics are made from non-renewable resources such as natural gas and crude oil, using almost 500 million tonnes of carbon dioxide per year; bioplastics, however, do not exploit these resources and reuse organic waste instead. Hence, bioplastics help solve the depletion of fossil fuels and organic waste disposal at the same time (Anjoran, 2020). However, bioplastics are limited in terms of their mechanical strength, and as a result, glass and carbon fibres are used to reinforce them. Glass and carbon fibres are not biodegradable, and this beats the purpose of using bioplastics. At the same time, plastics such as PHAs are being developed from enzymatic and chemical processes and have the potential to replace conventional plastics, matching them in thermal and mechanical properties (Coppola et al., 2021). Bioplastics are not cost competitive to conventional plastics as their costs are almost 2 or 3 times more, but this disparity becomes less significant in large manufacturing plants such as Braskem's 200,000 tonne bio polyethene plant (Anjoran, 2020). There is a misinformed notion that bioplastics based on terrestrial crops could limit food production; however, in reality, bioplastics use less than 0.02% of all agricultural land (Gammage, 2022). Moreover, it has been proven that 0.45 kg of PLA based bioplastics can be generated from 1 kg of PLA based biowaste (Lombardi et al., 2023). Maharashtra generates 22632.71 TPD of MSW, which is classified under PLA based polymers (Table 3). Hence, roughly 10184.72 TPD of PLA based bioplastics can be generated from the current waste being generated in Maharashtra, considering all waste is converted to biowaste.

Table 2 Degradation test for Potato Peel Bioplastic (Goswami et al., 2015)

Number of days	Observation for degradation		
	Wt. of Potato peel bioplastic (PPB) / g	Wt. Of Paper / g	Observation
1	8	8	No degradation
3	6.2	5.2	Degradation starts
5	5.8	3.2	Paper degraded, PPB slowly degrading
7	4.9	2.0	Rate of degradation slows down
9	3.5	-	Degradation slows down
Under same conditions of soil, temperature, and humidity			

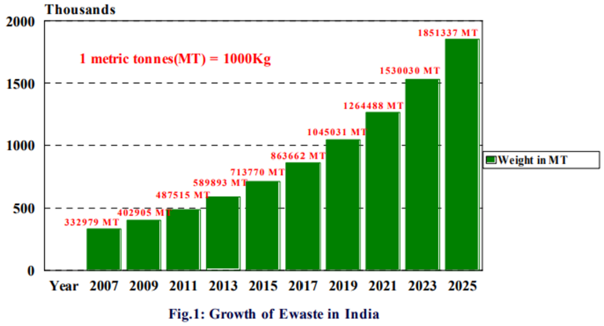

Fig. 9 Growth of e-waste in India (D. S. Chatterjee, 2011)

Electronic-Waste

Electronic waste (E-waste) consists of "discarded and end of life electronic products ranging from computers, equipment used in information and communication technology (ICT), home appliances, audio and video products" (D. S. Chatterjee, 2011). In India, e-waste is generated at a faster rate than plastic waste and 1.014 million tonnes were produced in 2019-2020, with a 31% increase (Figure 9) each year (Recykal, 2022). Maharashtra produces the most e-waste state-wise, while Mumbai produces the most e-waste city-wise (Figures 10 and 11) (D. S. Chatterjee, 2011). However, 95% of e-waste is illegally handled by the informal sector by ragpickers (Recykal, 2022).

E-waste is informally disposed of by dismantling, shredding, and melting. These processes release dust particles and toxins which cause air pollution and damage respiratory health (Elytus, 2018). Elements such as lead can cause damage to human blood, kidneys and central and peripheral nervous systems (Lubell, 2018). Moreover, when e-waste is dumped in open dumps or landfills, heavy metals and flame retardants can seep into the soil and cause contamination of groundwater and crops near that area (Elytus, 2018). Refrigerators, air-conditioners, and similar equipment contain ozone depleting substances such as CFCs and HCFCs and therefore have a very high global warming potential. Hence, they need to be discarded in an environmentally safe manner (Mathias Schluep et al., 2009).

E-waste is largely made up of metals as modern electronics such as cell phones contain over 40 different elements (Figure 12) such as copper (Cu), tin (Sn), silver (Ag), gold (Au), and palladium (Pd). An average phone would contain 250 mg

Table 3 Different types of biological wastes that have been used for production of bio based plastic (George et al., 2021)

Type of Waste	Examples of Bio Waste	Type of Plastics Produced
Lignocellulosic biowaste	Sugarcane bagasse, cotton linters, corn cob, corn husk, rice husk, rice straw, wheat bran	Cellulose Based bioplastics and PHB polymers
Food industry biomass waste	Peel waste: Cassava, potato, pineapple, orange, and banana peels	Starch based bioplastics and Cellulose based bioplastics, PLA and PHB polymers
	Seed waste: Mango, Date, Avocado, Jackfruit	Lipid based bioplastic, Starch based bioplastic, PHB polymers
	Crustaceans' shells waste: shells waste from squilla, shrimp, crab, lobster, prawn like crustaceans	Chitin based bioplastic and nanostructured film
	Waste oil: Waste frying oil, Nonedible oil like Castor and Jatropha	Lipid based bioplastic, and PHA polymers
Biowaste from effluents	Domestic wastewater, Food and dairy industry wastewater, Wood mill effluent, Oil industry effluent	PHB, PHA, poly-3-(hydroxybutyrate-co- hydroxy-valerate) and PHA polymers
Miscellaneous waste	Municipal solid waste Feather quill Paper waste	PHA, Protein based bioplastics, PLA polymers

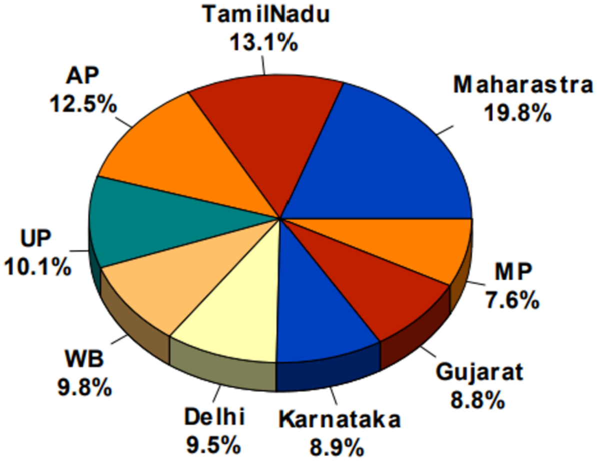

Fig. 10 State-wise e-waste generation in India (D. S. Chatterjee, 2011)

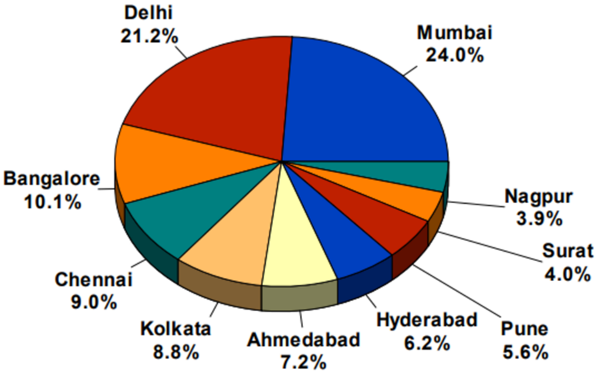

Fig. 11 City-wise e-waste generation in India (D. S. Chatterjee, 2011)

Ag, 24 mg Au, 9 mg Pd, and 9 g Cu. These numbers may look underwhelming; however, when the global number of 14.91 billion mobile devices (2021) is considered (Laricchia, 2023), this leads to an extremely significant demand for metals. When e-waste is not disposed of using proper methods, it not only leads to negative environmental effects, but also a waste of metals which could be reused. Primary production of metals including mining, concentrating, smelting, and refining causes a large release of carbon dioxide as well. If disposal is done in an environmentally favourable manner, only a fraction of the energy used in primary production would be required in its production, further cutting down on pollution and wastage of resources (Mathias Schluep et al., 2009). The technologies of integrated smelter-refinery for disposal of printed wiring boards and electric arc furnace for disposal of ferrous materials are used.

Integrated Smelter-Refinery Printed Wiring Boards (PWBs) and small electronic devices (mobile phones and MP3 players after the removal of the battery) contain both precious metals and toxic/hazardous substances. The precious

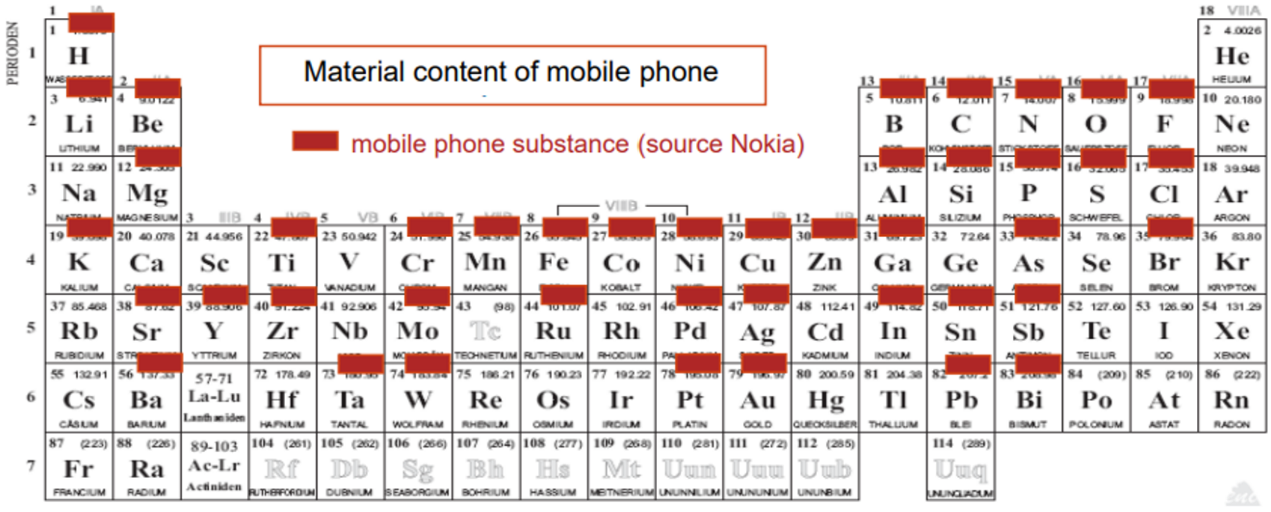

Fig. 12 Element content in mobile phones (Mathias Schluep et al., 2009)

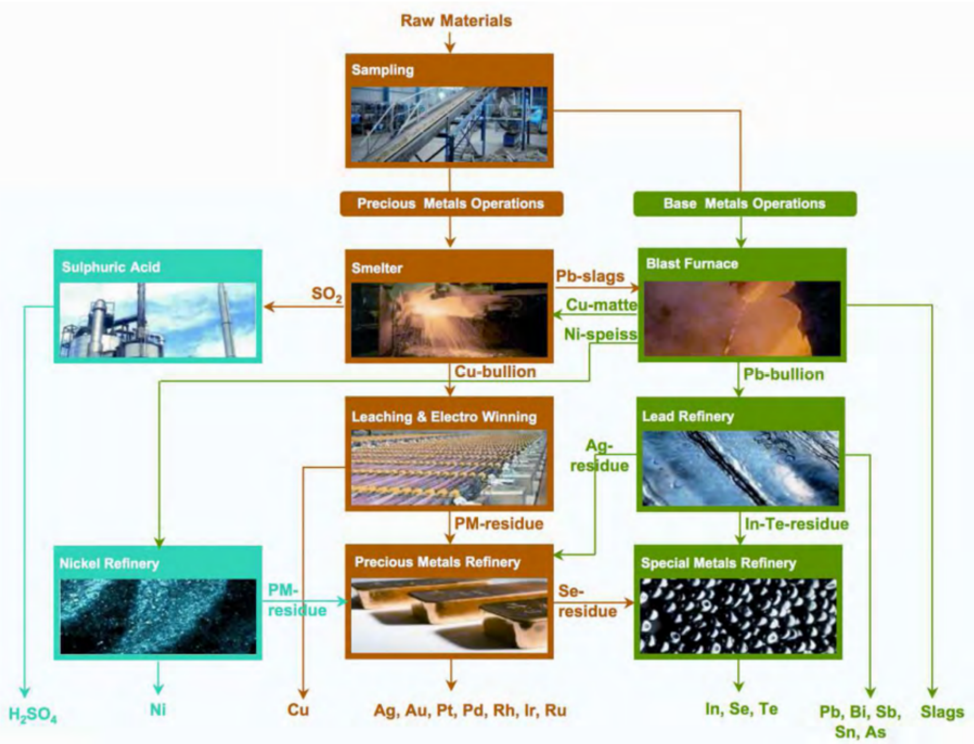

Fig. 13 Integrated smelting/refining operations (Mathias Schluep et al., 2009)

metals can be extracted and sold, while the toxic/hazardous substances are extremely detrimental to the environment. A typical PWB from a PC would contain 7% Fe, 5% Al, 20% Cu, 1.5% Pb, 1% Ni, 3% Sn and 25% organic compounds, with traces of As, Sb, Ba, Br and Bi. The following process (Figure 13) is used:

i Integrated smelter-refinery: the smelter uses a smelt submerged lance combustion technology and has extensive off-gas emission control installation and processes over 1,000 tonnes of feed material per day. Enriched air and

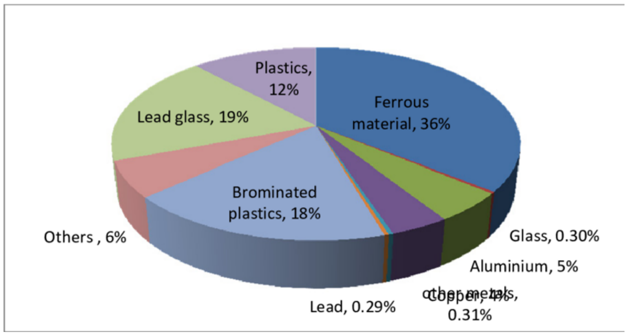

Fig. 14 Composition of e-waste (Senophiyahmary & Thirumoorthy, 2016)

fuel are injected through a lance in a liquid bath and coke is added for chemical reduction of the metals at 1200 °C. Organic compounds play an important role as a reducing agent and fuel and are classified as feedstock recycling. Thorough stirring of the copper metal and the lead slag phase and blowing air guarantee rapid chemical reactions.

ii Leach-electrowinning plant and blast furnace:

  a a. Leach-electrowinning plant: The copper goes to the leach-electrowinning plant, combining hydro and electrometallurgy. Sulfuric acid dissolves granulated copper and results in copper sulphate solution, while the precious metals are in a concentrated residue. The copper sulphate solution is sent to the electrowinning plant for electrolysis in order to recover the copper. The precious metals residue is then refined at the precious metals' refinery. Pyro and hydrometallurgy are used to recover Ag, Au, and platinum group metals at the refinery.

  b b. Blast furnace: The lead oxide slag contains Pb, Bi, Sn, Ni, In, Se, Sb, As and some Cu and precious metals and is treated in the blast furnace. It produces approximately 200-250 tonnes/day of lead bullion (95% lead), and precious metals are collected. Other by-products include copper matte, nickel speiss, and slag. Copper matte is returned to the smelter, nickel speiss is sent to the nickel refinery, and slag is used as a construction material for concrete.

This integrated process has high success rates with a gold recovery of over 95%; useful products obtained such as Pb, Sb, As; and toxic products including Hg, Be, and Cd captured. The process results in less than 5% of the feed materials being converted into a waste, significantly lower than the initial waste (Mathias Schluep et al., 2009).

Electric Arc Furnace (EAF)

Ferrous Metals are metals which contain iron and are the biggest percentage of Indian e-waste, accounting for 36% of the total e-waste (Figure 14). Hence, it is essential to consider the disposal of ferrous metals. EAFs are then fed with scrap materials and electricity is used to remelt it. The EAF process can be divided in five subprocesses: pre-treatment, charging, melting, alloying, and tapping, as explained below:

i Pre-treatment: The e-waste must be treated by removal of metallic copper, lead, and tin alloys as these are undesired elements in the remelting process.

ii Charging: The EAF is charged with scrap metals and other post-consumer steel waste such as from end of life vehicles and beverage cans (Mathias Schluep et al., 2009).

iii Melting: Carbon and slag formers (lime-carbon mixture) could be added to prevent overoxidation of the steel and to quicken slag formation. The meltdown process begins with a low power setting till all of the material is melted with the electrodes reaching the top of the charge. After melting, the carbon level in the steel is 0.25% above the tap level, preventing over oxidation. The slag formed consists of 55% lime, 15% silica, and 15% to 20% iron oxide (Britannica, 2001).

iv Alloying: The slag is removed from the first oxidizing meltdown and new slag formers containing carbon and aluminium as reducing agents are added. The new slag would contain 65% lime, 20% silica, 15% calcium carbide or alumina and no iron oxide. Alloys such as chromium and nickel which can oxidise easily are added to improve metallurgical control. The refining then continues till the heat is ready for tapping.

v Tapping: Once the steel has reached the desired chemical composition, the steel is tapped from a furnace and into ladle treatment stations, where it is then transported to casting machines and cast into slabs, among other shapes (Britannica, 2001).

Plastic

The OECD reports that the world is producing twice as much plastic waste as it was 20 years ago, with most of it ending up in landfills, incinerated, or leaking into the environment and only 9% of it is recycled (OECD, 2022a). It is, therefore, necessary to implement sustainable technologies to safely dispose of plastic waste. Plastic can be converted into plastic roads, solving the problem of urbanization and waste disposal at the same time.

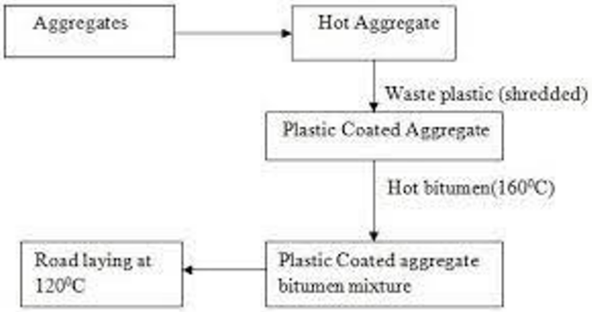

Fig. 15 Flow diagram of dry process (Yadav & Chandrakar, 2017)

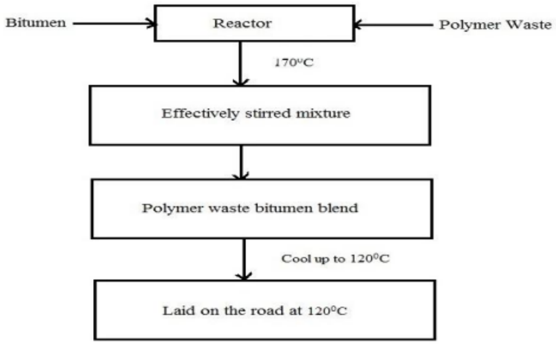

Fig. 16 Flow diagram of wet process (Yadav & Chandrakar, 2017)

Plastic Roads Plastic roads have a higher resistance to deformation, water induced damages, and have increased durability and fatigue life, and lesser potholes (Table 4). Hence, plastic roads are more durable and would result in lesser costs for renovation as well as smoother roads for civilians. At the same time, it utilizes plastic waste. Plastic waste is extremely difficult to recycle and dispose of sustainably, so plastic roads deal with 2 problems at once (S. Singh, 2019). Massive transport infrastructure projects such as the coastal road and trans harbour sea link in Mumbai require 10.58km and 21.8km of roads respectively and plastic roads could be used to fulfil this growing need. Plastic roads also decrease the need for bitumen by 15-20% and reduce the cost of the construction of roads. Moreover, it generates jobs for rag pickers in India (Civil Guruji, 2022). This technology has been used in Tamil Nadu, Chennai in 2002 and roads of over 1,000km were constructed using plastic waste in Tamil Nadu. It has also been used in 2,000km of roads in Bangalore (Nirmal, n.d.). However, plastics could still be toxic or contain chemical materials which would cause environmental pollution, heating plastics may release toxic emissions which humans are susceptible to, and microplastics could reach the river, causing a threat to marine life (Nirmal, n.d.). Plastic polymers such as polypropylene and polyethylene can be broken down due to heat, hydrolysis, mechanical shear, oxidation, and pollutants including carbon dioxide and sulphur dioxide. Furthermore, due to the phase separation and poor chemical compatibility between plastic polymers and bitumen, plastic can leach out, polluting the environment and reduce the durability of the roads (Abd Karim et al., 2023). Therefore, there are still some impacts on the environment that need to be considered while utilising plastic roads. India has made various improvements to do with the quality of plastic being used. On 12th August 2021, the manufacture, import, and sale of single use plastics was banned, with effect from 1st July 2022 (Sai Ram et al., 2022). This step was pivotal as single use plastics are non-biodegradable and stay in aquatic and terrestrial ecosystems for years, causing a lot of harm. Furthermore, plastic bags of less than 120 microns were banned from 1st January 2023 as microplastics can enter the food chain and degrade human health and disrupt ecosystems and the environment (TOI, 2022). Hence, India is on its way to improving the quality of plastic used and this will inevitably increase the quality of plastic roads, their strength, durability, and will pollute the surrounding environment less. All in all, plastic roads are a developed technology which can easily be applied to Mumbai and would help dispose of the building up plastic waste.

Table 4 Comparison of plastic and ordinary roads (S. Singh, 2019)

Properties	Plastic Roads	Ordinary Roads
Marshall Stability Value	More	Less
Binding Property	Better	Good
Softening Point	Less	More
Penetration Value	More	Less
Tensile Strength	High	Less
Rutting	Less	More
Seepage Of Water	No	Yes
Durability Of Roads	Better	Good
Potholes	No	More

i Dry Process:

  a Heating of aggregate: The aggregate mix is heated to 165-170 °C.

  b Shredding: The collected plastic waste is cut and shredded into a size of 2.36mm to 4.75mm using a shredding machine.

  c Coating aggregate bitumen mixture with plastic: Shredded plastic is added over the hot aggregate with constant mixing to ensure a uniform distribution.

d Road laying: The mixture is then laid on the road at 120°C (Civil Guruji, 2022; Rastogi, 2017).

ii Wet Process:

a Adding and heating of plastic waste and bitumen: the waste plastic is directly added to bitumen and is heated to 170°C.

b Mixing: the mixture is stirred to ensure a uniform distribution.

c Cooling: the hot mix is cooled to 120°C in another chamber and is then added to the aggregate in the paddling chamber. It is cooled as air pockets could form in small gaps of aggregate, leading to lower road strength and rutting of roads.

d Road laying: A modified bitumen is added and is then laid on the road followed by spreading the material by a 8 tonne roller (Yadav & Chandrakar, 2017).

Recommendations

Following exhaustive review of the technologies emerging to combat waste accumulation, this study would recommend that the anaerobic digester technology is implemented in Mumbai. Organic waste accounts for 57% of the waste generated in Mumbai (Kaza et al., 2018) and anaerobic digesters would make an immediate change to the amount of waste treated, as it would not only sustainably dispose of organic waste but also produce biogas and digestate which acts as a rich fertilizer when treated. AD may be more expensive than composting and vermi-composting due to heating and mixing but the biogas produced can cut down on the operational costs and can serve as a renewable gas. Furthermore, AD is a highly mature technology (Table 5) and is in place at large capacities in the USA, Europe, and China (Akhiar et al., 2020).

Furthermore, this study would further recommend that the integrated smelter-refinery technology is implemented for e-waste, as it is a mature technology and can be used without any doubts of its working (Table 5). This study would suggest that the plastic road technology is implemented for plastic waste as it has already been used in Indian cities including Chennai and Bangalore (Section 4.3.1) and is in its growth stage of maturity (Table 5). This would ensure that all major types of waste generated in Mumbai have sustainable technologies for disposal.

This study will consider AD, the recommended technology for disposal of organic waste, and calculate the total biogas produced by AD based on the current organic waste outputs by Mumbai and calculate the total capacity of the AD plants needed.

Table 5 Summary of all technologies based on the type of waste they dispose of and their maturity.

Technology	Type of waste	Maturity
Plasma Pyrolysis	Organic, Plastic, Medical, Industrial, and Electronic	Growth
Plasma Gasification	Organic, Plastic, Medical, Industrial, Electronic, and Hazardous	Growth
Anaerobic Digestion	Organic	Mature
Microbial Fuel Cells	Organic	Emerging
Bioplastics	Organic	Growth
Integrated Smelter Refinery	Organic, Electronic, Industrial, Hazardous	Mature
Electric Arc Furnace	Industrial, Electronic, Metallic	Mature
Plastic Roads	Plastic	Growth

Calculations for anaerobic digesters in Mumbai (Vögeli et al., 2014; Zurbrügg, 2018):

Values and assumptions used while making calculations:

- Mumbai population – 21,297,000 (Macro Trends, 2019)
- Waste generation rate in India – 0.57 kg/capita/day (Kaza et al., 2018)
- Total solid (TS) – 20%
- Mixing with one part waste and two parts water
- Volatile solid (VS) – 20% of TS
- Retention time – 30 days
- Biogas yield for vegetable waste – 0.67 m3/kg
- 75% of the digester is the slurry and 25% is the gas holder

Feedstock:

$$21,297,000 \times 0.57 kg/capita/day = 12139.29\ kg/day \quad (1)$$

$$Organic\ Waste = 57\% \times 12,139.29 = 6919.3953\ kg/day \quad (2)$$

Amount of feedstock

$$= 6919.3953 + 2(6919.3953)$$
$$= 20758.1859 L \qquad \text{(assuming that 1L=1kg)} \quad (3)$$

Retention time (assume retention time to be 30 days in a tropical climate):

$$\begin{aligned}\text{Volume of digester} &= 20758.1859 L/day \times 30\, days\\ &= 622.745577 m^3 \end{aligned} \tag{4}$$

Feedstock quality:

$$\begin{aligned} TS &= 6919.3953\, kg \times 20\%\\ &= 1383.87906\, kg \text{ dry matter} \end{aligned} \tag{5}$$

$$\begin{aligned} VS &= 1383.87906\, kg \times 80\%\\ &= 1107.103248\, kg\, VS/day\ per\ 36417.87L \end{aligned} \tag{6}$$

$$Total\ VS = \frac{1107.103248}{20758.1859} \times 1000 = 53.3\, kg\, VS/m^3 \tag{7}$$

Organic loading rate (OLR):

$$\begin{aligned} OLR &= \text{substrate flow rate } m^3/day\\ &\times \frac{\text{substrate concentration } kg\, VS/m^3}{\text{reactor volume } m^3} \end{aligned} \tag{8}$$

$$OLR = 20.7581859 \times \frac{53.36}{22.745577} \tag{9}$$

$$OLR = 1.78 \text{ kg VS/m}^3 \tag{10}$$

Amount of gas:

$$\text{Biogas yield for vegetable waste} = 0.67\, m^3/kg\, VS \tag{11}$$

$$\begin{aligned} &= 1.78\, kg\, VS/m^3 \times 0.67\, m^3/kg\, VS \times 622.745577\, m^3\\ &= 742.686375\, m^3/day \end{aligned} \tag{12}$$

Total volume of unit:

$$\begin{aligned} 622.745577 \text{ m}^3 \text{ slurry} + 207.581859 \text{ gas} &= 830.327436 \text{ m}^3\\ &\approx 830.3 \text{ m}^3 \end{aligned} \tag{13}$$

Therefore, 830.3 m^3 is the hypothetical volume of an anaerobic digester if all of the organic waste was disposed of by only one digester. However, in reality, there will be a large number of digesters and this figure will get divided in between them. 830.3 m^3 is far too large for a single anaerobic digester.

Limitations

This study was able to provide a description of each technology, the processes behind it, and an analysis of the technology. However, since various technologies are being considered, information has been kept precise to provide a comprehensive understanding of each technology. Based on technology maturity and effectiveness, AD was chosen to dispose organic waste in Mumbai. While calculations about the amount of biogas that can be formed have been made, it is done assuming that all organic waste is treated with AD. In reality, however, no one technology will be able to dispose the waste generated by a megacity such as Mumbai. It will be difficult to produce the same technology in different parts and, hence, composting and vermi-composting will inevitably be used as alternatives to treat organic waste. Therefore, this study only considers the case when all organic waste uses AD. Furthermore, calculations have not been made for E-waste or for plastic waste.

Conclusion

This paper evaluated the current state of waste disposal in Mumbai and suggested possible sustainable and emerging technologies for disposal of organic, electronic, and plastic waste with entire processes and advantages and disadvantages allowing one to weigh the technologies against each other and work out the technology best suited to one's needs. This was followed by calculations for the most mature technology for organic waste disposal – anaerobic digestion – successfully giving an idea of the required size of the plant, according to the waste composition and generation of Mumbai, and the amount of biogas produced from the waste input. Hence, the paper has provided the basic tools and resources to go forward with implementing technologies for a sustainable waste management system with using Mumbai as a case study.

List of abbreviations:

SWM – Solid Waste Management
MSW – Municipal Solid Waste
CPCB – Central Pollution Control Board
MoEF and CC – Ministry of Environment, Forest, and Climate Change
AD – Anaerobic Digestion
C/N Ratio – Carbon to Nitrogen Ratio
MFC – Microbial Fuel Cell
E-Waste – Electronic-Waste
CFC – Chlorofluorocarbon
HCFC – Hydrochlorofluorocarbons
PWB – Printed Wiring Boards
EAF – Electric Arc Furnace

OECD - Organisation for Economic Co-operation and Development
TS – Total Solid
VS – Volatile Solid
OLR – Organic Loading Rate

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