A review on integrated approaches for municipal solid waste for environmental and economical relevance: Monitoring tools, technologies, and strategic innovations

Nidhi Kundaria[1,2], Swayansu Sabyasachi Mohanty[1,3], Sunita Varjani[1,*], Huu Hao Ngo[4], Jonathan W. C. Wong[5], Mohammad J. Taherzadeh[6], Jo-Shu Chang[7,8,9], How Yong Ng[10], Sang-Hyoun Kim[11], Xuan-Thanh Bui[12,13]

[1]Gujarat Pollution Control Board, Gandhinagar-382 010, Gujarat, India

[2]Kadi Sarva Vishwavidyalaya, Gandhinagar, Gujarat - 382015, India

[3]Central University of Gujarat, Gandhinagar- 382030, Gujarat, India

[4]Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, NSW - 2007, Australia

[5]Institute of Bioresource and Agriculture, Hong Kong Baptist University, Hong Kong

[6]Swedish Centre for Resource Recovery, University of Borås, 50190 Borås, Sweden

[7]Department of Chemical Engineering and Materials Science, College of Engineering, Tunghai University, Taichung, Taiwan

[8]Research Center for Smart Sustainable Circular Economy, Tunghai University, Taichung, Taiwan

[9]Department of Chemical Engineering, National Cheng Kung University, Tainan, Taiwan

[10]National University of Singapore, Environmental Research Institute, 5A Engineering Drive 1, Singapore 117411, Singapore

[11]School of Civil and Environmental Engineering, Yonsei University, Seoul, 03722, Republic of Korea

[12]Faculty of Environment and Natural Resources, Ho Chi Minh City University of Technology (HCMUT), Ho Chi Minh City 700000, Vietnam

[13]Key Laboratory of Advanced Waste Treatment Technology, Vietnam National University Ho Chi Minh (VNU-HCM), Linh Trung ward, Thu Duc district, Ho Chi Minh City 700000, Vietnam

*Corresponding author: drsvs18@gmail.com; ORCID ID: 0000-0001-6966-7768

Abstract:

Rapid population growth, combined with increased industrialization, has exacerbated the issue of solid waste management. Poor management of municipal solid waste (MSW) not only has detrimental environmental consequences but also puts public health at risk and introduces several other socioeconomic problems. Many developing countries are grappling with the problem of disposing of large amounts of produced municipal solid waste, as well as the need for a credible renewable energy source. Unmanaged municipal solid waste pollutes the environment, so its use as a potential renewable energy source would aid in meeting both increased energy needs and waste management. This review investigates emerging strategies and monitoring tools for municipal solid waste management. Waste monitoring using high-end technologies and energy recovery from MSW has been discussed. It comprehensively covers environmental and economic relevance of waste management technologies based on innovations achieved through the integration of approaches.

Keywords: Waste management; Municipal Solid Waste; GSM/GPRS; Innovations; Hazard Monitoring tools

1. Introduction

One of the most pressing issues today is the safeguarding of human civilization against the perilous effects of man-made waste (Banerjee et al., 2019). Municipal Solid Waste Management (MSWM) is one of these issues that need to be addressed right away. MSW mainly comprises of residential waste, yard waste, and Construction and Demolition (C&D) waste collected from houses, schools, hospitals, and business locations. Types of solid wastes and their effects on environmental and human health are shown in Figure 1.

************Insert Figure 1************

The management of Municipal Solid Waste is one of the biggest challenges to both developing and developed countries. In Sri Lanka, solid waste piling has increased dramatically in most urban areas, particularly in larger cities. Open dumping was reported to be the most commonly used MSW management strategy, accounting for approximately 85 % of the total waste collected (Saja et al., 2021). The improper disposal of MSW pollutes streets, water bodies, and other areas, worsening the current situation. Similarly, India, which ranks second among the world's most populous nations, produces around 0.15 million tonnes of MSW/day, of which approximately 90 % is collected (Malav et al., 2020). However, the lack of segregation of MSW and the use of open dumping for MSW management has exacerbated the problem in dealing with it.

The generation of MSW is a result of unsustainable use of natural resources that leads to source diminution and environmental degeneration (Mohammadi et al., 2019). It includes (a) non-degradable wastes like plastic, metals, rubber, e-waste, and (b) degradable wastes like paper, food, vegetables, and textile waste (Bhat et al., 2014; Mishra et al., 2021). The complexity and quantity of municipal solid waste generated are generally influenced by economic growth, urbanization (Mamun et al., 2016), and high living standards (Bhat et al., 2018). Furthermore, due to the absence of a proper solid waste management system, most of the waste is improperly segregated, collected, and transported (Abdel-shafy and Mansour, 2018). Other factors that influence solid waste management system include (a) local people's attitude toward waste (Agyeiwaah, 2020), (b) relationship between governance, (c) political stability, and (d) lack of informational communication between the people and the committee of the solid waste management system. Waste management is a critical concern these days, so there is a need to develop a system that is both sustainable and economical (Varjani and Upasani, 2016; Pujara et al.,2018; Harris-Lovett et al., 2019; Yaashikaa et al., 2020). The goals of solid waste management are to improve the environmental quality of urban areas,raise economical evolution, promote awareness regarding health and hygiene issues caused by improper waste management (Abdel-shafy and Javadian,2018). Inadequate municipal solid waste segregation and removal result in all types of pollution, including soil, water, and air. Furthermore, improper dumping of MSW pollutes surface and groundwater, whilst unscientific removal of MSW has a detrimental environmental effect (Varjani, 2017; Istrate et al., 2020).

The majority of urban solid wastes are discharged into bodies of water and soil without or improper treatment, which is the primary cause of much environmental pollution (Varjani et al., 2021a). Indian government has devised numerous programs to combat this type of pollution. For example, in 2014, the Government of India launched the Swachh Bharat Mission, which aims to strengthen the capacity of ULBs to design, implement, and execute all systems related to service requirements to guarantee cleanliness with respect to scientific MSWM. Other government policies, such as the Solid Waste Management Rules, 2016, offer additional specific guidance on different aspects of MSWM and designate the Central and State Pollution Control Boards as nodal agencies to supervise its implementation.

In such circumstances, WtE technology would be the best alternative for accessing alternative fuels. These technologies can generate a significant amount of heat and energy from waste, thereby reducing a lot of critical environmental issues associated with MSWM. Energy recovery from MSW may be achieved using thermochemical and biochemical processes (Fernández-Gonzalez et al., 2017). Waste-to-energy (WTE) approaches would be the right alternative for acquiring renewable sources of energy (Moya et al., 2017; Rene et al., 2020). In recent times, waste management investigators have studied various types of technology to improve waste management efficiency and automate bin collection. There have been attempts by researchers to investigate the possibility of introducing advanced systems for SWM based on identification technologies to solve the problems with manual data collection. Waste monitoring is crucial for the growth of the urban economy in the present world, mainly in developing nations. The abundance of sensing technologies like GSM/GPRS, sensors, and RFID has given MSW systems a new lease on life.

This paper discusses various aspects of MSW generation and management globally, with a focus on India. Furthermore, it highlights creative waste management solutions that have been established in many countries for achieving smart and effective waste management plans while addressing the various difficulties and shortcomings in these programs including if the waste is managed properly, how it results in economic and environmental benefits. Furthermore, the paper discusses use of high-end waste monitoring technologies such as sensors, RFID (radio frequency identification), geographic information systems, and an international structure for GSM/GPRS (Mobile/general radio packet service).

2. Municipal solid waste generation and management:

The quality and quantity of municipal solid waste depend on the factors such as pollution compactness, life anticipation, earning per head education, and human development (Azam et al., 2020). The volume, weight, and density of solid waste vary from place to place (Cheng et al., 2020; Alidoust et al., 2021). Geographical factors like location of the country, climate and weather conditions, socio-economic conditions including income, living conditions, and lifestyle also play a significant role in it (Scarlat et al., 2019; Sharma and Jain, 2019).

2.1. Global and national scenario:

The urban population of the world is growing at a faster rate (1.5 percent) than the global population (Das et al., 2019). Since cities now house over half of the global population, urbanization, population growth, and economic development are all contributing to the global increase in MSW generation. Global MSW production is more disastrous and is estimated to exceed 2,200 million tonnes/year by 2025 (Tyagi et al., 2018).The world generated approximately 2.01 billion tonnes of waste in 2016. According to projections, it will rise even further. Based on the current World Bank report, it will be around 2.59 billion tonnes by 2030 and 3.40 billion tonnes by 2050 (ADB, 2020). Table 1 shows the major contributory countries in terms of solid waste production and disposal on a global scale (Pujara et al., 2019).

**************Insert Table1************

With a 5% annual growth rate, India's 1.36 billion people are estimated to produce over 56 million tonnes of Municipal Solid Waste per year (Pujara et al., 2019). India has produced a large amount of waste in recent years. The country produced approximately greater than 52000000 MT of MSW in 2017-18, which increased to 53175755 MT in 2018-19. However it showed a significant decrease in MSW generation in 2019-20, which was nearly 32773470 MT of MSW (Tabular Data, 2021). The reduction in MSW generation may be primarily due to the closure of industries, institutions, businesses, and restaurants as a result of the countrywide lockdown during the pandemic.

Organic constituents (70-80 percent) dominate the mixture of commercial and domestic waste(s) in Indian Municipal Solid Waste, with inorganic compounds accounting for the remainder (Ramachandra et al., 2018). As a result, direct landfill dumping of MSW (without pre-treatment) causes several environmental problems, including the release of Green House Gases (GHGs) and toxic Volatile Organic Compounds (VOCs), as well as groundwater pollution from leaching and sludge (Ramachandra et al., 2018; Patil et al., 2017; Hameed et al., 2021). Except for a few Indian metropolises, direct combustion (Mittal et al., 2017) and disposal at landfills without pre-treatment are widely used in India (Rathore et al., 2020; Rana et al., 2019). The United States ranks first in the world in terms of per capita/per day/MSW generation, at a rate of 2.58 kg (Wong, 2020). This generation drops to around 0.73 kg in China (Zhu et al., 2020). Whereas, in a single day, the metropolis towns and cities of various Indian states generate 0.5 kg Municipal Solid waste per person.

3. *Environmental and economical relevance*

Management of solid waste is a critical component of environmental impacts and related economic consequences (Varjani and Upasani, 2021). Along with the monetary value which is levied on the remediation technology, mismanagement of MSW greatly hampers the aesthetics of the natural surroundings (Adesra et al., 2021; Zorpas, 2020). Environmental and public health consequences can occur at the regional and local levels as a consequence of poor waste collection, substandard waste handling and a lack of infrastructure (Gallardo et al., 2015; Gupta et al., 2015; Varjani et al., 2021a). In many low- and middle-income countries, improper waste collection, as well as unregulated dumping or burning of solid waste, is still an ugly fact that pollutes the air, water, and soil.

Open burning and landfill disposal are still the most common MSW management practises in many Indian cities (Rana et al., 2019). Both of these strategies contribute significantly to air pollution. For example, open burning of 1 tonne of MSW produces around 1090 kg of CO_2 equivalent (Pujara et al., 2019). Similarly, for every tonne of MSW disposed of in a landfill, nearly 70 kilogrammes of CH_4 (equivalent to 1610 kg of Carbon dioxide) could be emitted (IEA Position Paper MSW, 2019). The emission of such vast quantities of dangerous gases not only impacts health of public but also contributes to global warming. Furthermore, such management practices are damaging to water and soil. The leachate created by MSW landfilling, for example, not only pollutes surface and ground water but also has significant health effects on humans.

Additionally, mismanagement of MSW leads to enormous economic costs since the recalcitrant nature of some contaminants present in MSW makes remediation more difficult and inefficient (Pasalari et al., 2018; Pandey et al., 2021). As a result, the outcome of remediation becomes unpredictable, and the cost of remediation technology increases. (Shah et al., 2021; Sharma et al., 2018). However, if managed properly, it can be cost-effective, especially in terms of the environment, because it reduces expense of remediation of numerous environmental constituents that might become polluted if adequate waste management procedures are not used. Furthermore, as a result of recent technological improvements, management strategies are becoming more cost-effective and environmentally friendly. However, stringent legislation and enforcement are required to improve MSW management.

4. *Valorization technologies of MSW*

Valorization technology is divided into two parts one is biochemical conversion and another one is thermal conversion. It entails thermal treating the organic matter in Municipal Solid Waste to generate thermal energy (Kumar and Samadder, 2017). This technology is typically beneficial for dry waste containing high concentrations of non-biodegradable organic matter (Yogalakshmi et al., 2022). Biochemical conversion technology relies on the microbial breakdown of MSW's organic content (Yaashika et al., 2020; Pandey et al., 2021). Organic Fraction of MSW includes food waste, kitchen waste, leaves, grass cuttings, flowers, and yard waste. This fraction of MSW is a prospective source for recovery of a variety of resources, including the generation of compost, as well as the production of biogas (Mohanty et al., 2021; Paritosh et al., 2018). Dealing with enlisted wastes using these methods not only helps to reduce the effect of MSW on the environment and economy but also paves the way for resource recovery, thus assisting in achievement of a circular economy (Venkata Mohan et al., 2020).

4.1. Biochemical conversion

4.1.1. Composting approach:

Waste management and control are a hallmark of an emerging and modern society (Varjani et al., 2017; Rajmohan et al., 2019). Solid waste generally contains degradable, non-degradable, and partially degradable materials. In developing countries, degradable waste makes up the larger part of solid waste which is generally characterized by high moisture content and needs proper management (Xue et al., 2019). Thus, composting is used as a biological treatment for solid waste management (Varjani et al., 2021b). Composting is defined as an microbial biochemical process under controlled conditions that increase the decomposition rate of organic matter (Vigneswaran et al., 2016; Thomas and Soren, 2020). Composting can convert solid waste into sanitary, stable, and non-polluting materials (Aziz et al., 2018; Pergola et al., 2018). Composting includes a serial microbial community that carry out decomposition of solid organic fraction into the water, carbon, minerals, and nutrient-rich stabilized compost (Rastogi et al., 2016; Manu et al., 2021). Major steps of composting are (a) An initial mesophilic phase, in which mesophilic bacteria and fungi quickly raise the temperature and carry out mineralization of simple compounds such as amino acids and sugars (carbohydrates) producing heat, CO_2, and water. This leads to partially stabilized organic waste, (b) The second is the thermophilic phase, in which thermophilic bacteria and fungi carry out the degradation of complex organic materials like cellulose, hemicellulose, lignin, and fats. Microbial reaction increases the temperature of the compost heap (Głąb et al., 2020). Heat amplest the rate of decomposition and inactivates the pathogenic microorganisms. Generally, bacteria of the genus *Thermus* are commonly noticed at the maximum compost temperatures.The cooling phase of composting is again colonized by mesophilic microorganisms that degrade remaining carbohydrate, hemicellulose, cellulose, and other humic substance (Albrecht et al., 2010). It is then followed by a reduction in the breakdown of organic material and a rise in the rate of humification and polymerization (Jain et al., 2020). Microbes are active agents during composting. Compost maturity and the rate of biodegradation are influence by the presence of certain microorganisms. Composting reduces the load on landfills and acts as a conditioner. Transportation cost is the major drawback of composting.

4.1.2. Vermicomposting:

Vermicomposting of municipal solid waste is gaining popularity these days because it adds value to the waste while also reducing volume, making it easier to use. Vermicomposting is the process of stabilizing organic solid waste by converting it to earthworm castings through consumption of waste by earthworms (Soobhany et al., 2017). Vermicomposting occurs when organic waste is degraded by gut microbes of earthworms, resulting in stable and mature vermicompost (Mengistu et al., 2018).Selection of appropriate earthworm species for vermicomposting is the most important step because it affects rate of waste stabilization. There are a variety of earthworm species that can be used in waste management (Balachandar et al., 2021).Table 2 shows the variety of earthworm species and their application in waste management.

*********Insert Table 2*********

The earthworm(s) can colonize organic waste naturally, have high rates of organic matter intake, absorption, and assimilation, and can withstand a wide range of environmental tension. In the waste mixture, earthworms maintain aerobic conditions, consume solids, and convert a portion of the organic matter into respiration products and biomass (Yuvaraj et al., 2021).Stable vermicompost improves microbial and physicochemical properties of soil and plant growth. One of the most effective methods for restoring soil productivity and managing organic waste is to use organic waste manure obtained by vermicomposting (Srivastava et al., 2020).

4.1.3. Anaerobic digestion:

Anaerobic digestion (AD) is used to recover energy from biodegradable and moist waste such as food waste(Liang et al., 2021)and livestock sludge (Malav et al., 2020; Luo et al., 2021). Anaerobic digestion is regarded as a credible process because of its economic and technical viability in comparison with other available techniques like pyrolysis, incineration, gasification, and composting (Kiyasudeen et al., 2016; Zamri et al., 2021; Prajapati et al., 2021). Also, anaerobic digestion has less impact on air quality and contributes to minimizing carbon dioxide emissions by producing energy to replace fossil fuels (Ong et al., 2019;Fan et al., 2018). AD utilizes microorganisms to convert biomass into biogas whose main constituent is methane and carbon dioxide (Scherzinger and Kaltschmitt, 2021).

Anaerobic digestion is carried out by hydrolysis, acidogenesis, acetogenesis, and methanogenesis processes/steps (Mahmudul et al., 2021). These steps are performed by hydrogenotrophic bacteria, acidogenic bacteria, along with acetogenic and methanogenic bacteria. The AD process begins with hydrolysis. It is a considerably slower step which can limit the overall digestion rate. Table 3 shows various reactions related to a different stage of anaerobic digestion.

*******Insert Table 3*******

The AD process employs a variety of substrates which are classified into industrial, agriculture, and community waste (Sharma and Chandel, 2017). Agricultural waste is the most widely used substrate for AD applications. In India, experience in treating solid organic waste by anaerobic digestion is limited, except manure and sewage sludge (Yap and Nixon, 2015). Municipal solid waste in India is rich in moisture and organic matter, it is well adapted for the anaerobic digestion (Banerjee et al., 2019). Anaerobic digestion can be classified into either dry or wet, depending on the amount of water in the slurry (Karthikeyan et al., 2018). Dry AD contains a low amount of liquid digestate than wet AD. Nutrients present in liquid digestate may be recovered through a variety of bio-refinery technologies(Somers et al., 2018). Solid digestate can also be used as compost and has the same benefits as an organic conditioner in soil application (Pappalardo et al., 2018; Logan and Visvanathan, 2019).

4.2. Thermochemical conversion

4.2.1. Incineration:

At first, incinerators were used to reduce waste's volume and protect humans & environment against hazardous pollutants (Makarichi et al., 2018), but not to recover energy (Brunner and Rechberger, 2015). Due to strict landfill disposal regulations, incineration is a prevalent method of disposal in developed countries (Scarlat et al., 2015; Kumar and Samadder, 2017). Incineration has other advantages than reducing the total output volume of waste and generating electricity while treating the waste, such as the use of ash from incineration plants in the building of highways and the manufacturing of cement (Wang et al., 2018). Incineration is most credible as well as cost-effective when used for mass combustion without pre-treatment for the generation of energy (Joseph and Prasad, 2020). The most significant advantage of incineration is the total elimination of organisms as well as mineralization of hazardous substances (Brunner and Rechberger, 2015). According to the World Bank, the average calorific value for successful incineration with energy production is estimated to be at least 1700kcal/kg (Das et al., 2019).

Incineration not only reduces volume of solid waste but also produces energy from burning waste (Materazzi and Foscolo, 2019). This technique does not require pre-treatment as it is an unprocessed method. Emissions from incineration plants contain several pollutants (SO_x, NO_x, CO_2, etc.) which require a highly expensive air control system. For example, particulate removal is commonly accomplished using fabric filters or electrostatic precipitators. Additionally, flue-gas control systems are primarily used to monitor NOx emissions. Selective noncatalytic reduction (SNCR), selective catalytic reduction (SCR), and wet flue-gas denitrification are examples of these techniques. All the above-mentioned techniques are very effective at removing concerned gases; however, the major drawback is that the combustion gas must be frequently reheated to the necessary range of temperatures to remove particulate matter (Waste incineration and public health, 2000).

4.2.2. Gasification:

Gasification is a thermochemical process that uses heat and a poor oxygen environment to convert carbonaceous material like biomass (Vaish et al., 2019; Fang et al., 2021). Gasification breaks down the MSW into a mixture of hydrogen, carbon monoxide, carbon dioxide, and small amounts of methane, generally known as synthetic gas (syngas) that has an energy content, and upon cleaning, it could be used to produce electricity in fuel cells or as fuel in engines and turbines (Ibrahimoglu et al., 2017; Vaish et al., 2019; Mukherjee et al., 2020). The H_2 and CO content of gasification reactions can be altered based on the reaction conditions. Syngas is also used in catalytic conversion for production of (a) chemical intermediates, (b) variety of liquid fuels, and (c) end products (Guran, 2018). The primary by-product of gasification is syngas, but other gases such as CO_2, CH_4, H_2O, and by-products such as char, tar, and ash particles are also formed (Ramos et al., 2020).

Most of the gasification studies deal with homogeneous solid fuel flow and the MSW (Putro et al., 2020). Gasification is widely used in Japan, while in other countries such as the United States, the United Kingdom, Germany and Norway, gasification is often used to treat MSW on a lower scale (Kumar and Samadder, 2017). The benefit of gasification technology is that it can minimize waste volume by up to 95 percent while requiring less intimate cleaning of combustion gases as compared to incineration (Usmani et al., 2020). The need for qualified labour and professional personnel is a major drawback of gasification. Another drawback is waste with too much moisture, which makes total energy recovery difficult.

4.2.3. Pyrolysis:

Pyrolysis is a method of heat-treating waste in an oxygen-free system for the generation of liquid, solid, and gaseous waste (Sipra et al., 2018). It is the high-temperature decomposition of organic waste (300ºCto 800ºC) without oxygen. The temperature variations depend upon the material present in the process (Sekar et al., 2021). For the removal of metal, glass, and inert materials pre-treatment is necessary for pyrolysis. It is a thermal process that degrades plastics and polymers containing major chain hydrocarbons without the use of oxygen.

Specific types of waste like tires, plastic, electronic materials, wood waste, and electric waste increase the quality of pyrolysis (Uzoejinwa et al., 2018).

Thermal decomposition of pre-treated waste at 300℃, without oxygen, is the first step of this process. Then in a non-reactive atmosphere temperature is increased up to 800℃. Pyrolysis is split into fast pyrolysis and slow pyrolysis based upon heat transfer (Malav et al., 2020).The primary outputs of these systems are energy, heat, bio-oil, and char. The char of pyrolysis is a source of solid fuel because it has a high calorific value (Mukherjee et al., 2020).The primary benefit of pyrolysis is that it requires a lower temperature than incineration and takes up less room. This strategy has a significant drawback in terms of money.

Velge et al. (2011) conducted slow and fast pyrolysis experiments with municipal solid waste as the feedstock to investigate the production of useful products. The experiment was carried out in a home-built semi-continuous lab-scale reactor. After completing the analysis, they discovered no waxy material in the slow pyrolysis liquid fractions, but a large fraction of waxy material and oil in the fast pyrolysis liquid fractions. As a valuable commodity, it can be used to make paraffin wax or, in the future, upgraded to lighter fuel fractions. Furthermore, qualitative analysis of the syngas generated during fast pyrolysis revealed that it has an average lower heating value. As a result, it demonstrated great potential for use as a fuel.

5. Innovations through the integration of approaches

Advancements in technology have led to new alternatives for an efficient use of MSW. There is a revolutionary method for making a form of "foam" from ceramic wastes which are both thermally and acoustically efficient. It's porous foam made of alginate that has been frozen dried at 80℃, primarily when Ca^{2+} ions are present. The use of rubber granulates which are obtained as a component to make new polymer composites are considered as environmentally sustainable and is one of the main methods for sustainable management of used tires. By recycling them this way, the quantity of tires after consumption is reduced. The rubber composites are primarily prepared by waste-free technology and have excellent mechanical and electrical capabilities with reasonable material economy construction (Sienkiewicz et al., 2017). A modern microbe-assisted electro-synthetic method for the effective retrieval of solvents such as alcohol sugar-rich waste has also been reported.

New technologies have also been developed to recycle upto half of the rubber waste, with techniques such as devulcanization serving as examples (Markl and Lackner, 2020). Rubber particles are mixed into crumbs using ultrasonic waves, making them easy to separate from bulk waste mixtures. Steel slag, bauxite red mud, and sludges are examples of industrial wastes that could be used to make paints, blocks, tiles, and sulfated cement. Das et al., (2019) emphasized on MSW-based filtration device capable of absorbing MX-3R, a yellow procion reactive dye. Hietala et al., (2018) described a technological innovation that creates fabric and yarn from plastic waste. This fiber is 10 times stronger than regular polyester fabric. The use of bottom ash in construction materials is a simple route for waste valorization (Elavarasan et al., 2020).

Flesoura et al. (2021), highlighted the use of bottom ash in concrete as an aggregate, landfill framework, embankment filler, and road-sub base product (Blasenbauer et al., 2020). Ho et al. (2019), examined use of alkaline hydrogen peroxide (AHP) in the pre-treatment of lignocellulosic biomass for biomass production. AHP pre-treatment can be used in a variety of lignocellulosic materials followed by enzymatic hydrolysis. The combined effect of hydrothermal and biological techniques can be convincing for biomass recovery by combining the advantages of both treatments to overcome the diversified and recalcitrant nature of biomass for a specific biochemical/biofuel platform(Song et al., 2021).

6. Municipal solid waste monitoring tools and technologies: Strategic innovations

6.1. Monitoring tools:

Monitoring waste generation is an essential phase in any region's or nation's waste management plan. Ultrasonic sensors, metal detectors, and aroma receptors are examples of technical interventions in the waste sector that allow safe and low-cost waste monitoring. After different waste fractions have been identified and separated, they can be easily sorted into stacks in a waste storage unit using mechanically operated sorting machines (Hannan et al., 2020). High-tech waste monitoring systems, such as sensors, RFID (radio frequency identification), geographic information systems, GSM/GPRS (Mobile/General Radio Packet Service) have been reported globally as efficient monitoring tools.

6.1.1 Radiofrequency identification:

RFID is an advanced information gathering technology that utilizes radio wave signals to transmit information between the transceiver and the transponder through inductive and back-broadcast correlation to identify a particular entity. This technology is centered on radio waves and has been used to monitor artifacts and individuals. One of the most popular methods of identification is to store a serial number as well as other details for a particular item on an RFID tag. The identification information can be obtained by scanning and reading the tag with an RFID reader. The RFID tag and reader communicate through radio waves, with the reader converting the reflected waves into digital data that is then sent to computers for processing. An RFID system is made up of three main parts: (a) a transponder, also known as an RFID tag, (b) an interrogator, also known as an RFID reader and (c) a host, which is an information gathering framework in a device. Hannan et al. (2011), suggested a waste bin and truck tracking system that used RFID. The RFID system has been used in European countries to determine the weight of the bin. Furthermore, the hardware and software used in this process are low-cost and require little effort to install and maintain (Catarinucci et al., 2019). Thus, RFID technology plays an important role in improving waste management efficiency (Abdullah et al., 2019). However, to use the bin, the individual must always have his or her identity card on hand. This is one of the limitations of this process (Mdukaza et al., 2018).

6.1.2 Global System for Mobile Communication/ General Packet Radio Service *(GSM/GPRS):*

The GSM/GPRS is known worldwide for digital cellular communication primarily used to transmit mobile use(Ali et al., 2020). Furthermore, GSM (Global System for Mobile Communication) provides data transmission facilities, with rates of data transmission limited to 9.6 Kbps and connection setup taking several seconds. GPRS (General Packet Radio Service) is considered as a type 2.5G network that is a GSM carrier service that greatly enhances and wireless access to the packet data network. GPRS utilizes the principle of packet switching, which can trace packets immediately from GPRS mobile workstation to packet switching network. The Internet Protocol (IP) and X.25 networks are both supported by GPRS. In India, this technique is used to monitor/manage municipal solid waste. However, in many other developing countries this technique has not yet been used to manage various types of wastes (Tsukiji et al., 2021).

6.1.3 Sensors:

A sensor is a tool that senses and tests actual characteristics of material such as physical quantities and chemical properties before converting them into signals which can then be directly seen or adopted by some other device. Solid waste management systems use a variety of sensors for data capture, rapid detection, and ambient surveillance (Hannan et al., 2015). A sensor is made up of two main components: (a) sensing element and (b) transducer element (Kumar et al., 2018). A measured amount is actively perceived or passively responded to by the sensing element. Even though popular sensors now transform calculated quantities into electrical signals, the part of transduction converts the determined number of physical processes into an appropriate analog signal for study (e.g., mechanic, electric, and optical).

The transduction element requires power to function. Furthermore, a signal binding and transformation element is required when dealing with a poor signal. There would be no automation without use of sensors.

Sensors are widely used in municipal solid waste applications(Singh, 2019). Vicentini et al. (2009), used sensorized refuse collection bins to optimize collection and estimate content. For solid waste collection, the bin tracking system employs weight, temperature, capacity, pressure, and humidity sensors. During various times of the year, the system has used measures to correlate municipal solid waste capacity with residential population and consumer index. MSW systems use a variety of sensors (volumetric, infrared, ultrasonic, capacitive and proximity) for measuring bin fill volumes to optimize routing and scheduling along with collection tracking (Bogomolov et al., 2015; Isgor et al., 2015; Sakurama et al., 2018; Wu et al., 2019). A load cell sensor (Mamun et al., 2016) and a strain gauge sensor were used to determine weight of waste inside the trash can. Resistive (Tripathi et al., 2018) and capacitive sensors (Isgor et al., 2015), as well as a tin oxide sensor (Ghosh et al., 2014), have been used to measure moisture and odor, respectively, for ambient condition monitoring. Optical sensors and infrared sensors are being used to separate glass waste and a variety of other municipal solid wastes. Furthermore, calorific value sensors have been used in incineration plants to track combustion (Yan et al., 2018). Various types of sensors are shown in Table 4.

********* InsertTable 4********

6.1.4 *Geographical information system (GIS):*

GIS is an advanced spatial system. It's a computer-based data collection, storage, management, integration, manipulation, analysis, and a system for displaying geospatial or geographically referenced data. The strength of GIS systems lies in their ability to organize these data into grid cells by creating digital maps. Visually analyzing data aids in the identification of trends, patterns, and relationships that may not be apparent in tabular or written form. A GIS typically has 4 types of components: (a) spatial data production, (b) data analytics, (c) geomorphology, and (d) display (Lu et al., 2013). GIS, when combined with other spatial and communication systems, aids in the capture, communication, and analysis of spatial data for designing and planning different applications (Jung et al., 2019).

It has been successfully used in the municipal solid waste management system. This technique has been used successfully in countries such as Australia and the Philippines. This technique was used to find an appropriate location for the application of animal waste, as well as to find suitable locations for the dumping of solid waste (Singh, 2019). Zsigraiova et al., (2013), introduced a new dynamic scheduling and navigation model integrating GIS to reduce MSW collection operation costs and pollutant emissions. GIS is an innovative approach for lowering operational costs and pollutant emissions associated with waste collection and transportation (Colvero et al., 2018).

6.2 Hazard monitoring:

Manual handling of solid waste materials has been linked to high levels of bacteria and endotoxins in the air, which can cause health problems (Grytnes, 2018). Risks arise at every stage of the process, from the point where workers collect or recycle waste in their workplaces to the point of final disposal. Diseases caused by dust and their symptoms are common, and they can last for decades. Ammonia, alkalinity, and Chemical Oxygen Demand are the most correlated parameters with toxicity in landfill leachates (Costa et al., 2018).Due to the complex composition of pollutants in leachate, traditional chemical monitoring becomes prohibitively expensive. Furthermore, after using solid-phase extraction (SPE) methods the isolated organic fractions of the leachate revealed toxicity associated with organic contaminants. Landfills(Zhang et al., 2019). Three-dimensional excitation-emission fluorescence (3D-EEMF) is a very sensitive and affordable option for monitoring organic matter as a quick, non-destructive chemical assessment tool (Pan et al., 2017). It has a lower operating cost than many other advanced technologies and can be used in developing as well as developed countries. UV-VIS spectrophotometric analyses may be more suitable in developing economies (Michalec and Tymecki, 2018).

7 Research needs and Future directions

The current energy output in many developing countries is considerably less than the real energy needed for consumption. Since fossil fuels are rapidly depleting, the world requires alternative energy sources, like WtE, to avoid future energy shortages (Moustakas et al., 2020; Jahnavi et al., 2020). Many developing countries face the issue of disposing of large amounts of produced MSW. There is a need for a credible renewable energy source. MSW pollutes the ecosystem when it is not handled properly, so using it as an alternative energy source would aid in meeting both increased energy needs and waste management. The main concerns in every country regarding health and sustainable development are adequate and effective waste management and disposal. Problems arising from existence of MSW can be significantly mitigated by adoption of environmentally friendly technologies. These technologies allow for the effective treatment of municipal solid waste before final disposal. Waste to energy technologies are the means of energy recovery from waste and are currently used in the market to produce fuel or electricity (Kumar and Samadder, 2017; Vrancken et al., 2017). Future studies should focus on eliminating the limitations/challenges of waste to energy technologies which are in practice nowadays. Many political, financial, and technical obstacles to Waste to Energy sector growth have been established, including a lack of funds, contradictory national policies and regulations, and poor data gathering & analysis. These disadvantages should be explored and debated to find their proper solution (Chand Malav et al., 2020). The public need to raise knowledge of appropriate prospects, such as the organization of a seminar(s)/events on the management of solid waste, understanding of the benefits of proper solid waste, and conduct surveys to understand the general population.

In today's world, waste monitoring is critical for urban development. Proper collection and sorting are vital for any municipal solid waste operation. Although informal rag-picking has been the most prevalent waste collection method, it has been linked to serious human health problems. Despite the rapid increase in research publications in this field many of the publications demonstrate that technological advancements in solid waste management are still in progress, with a critical need for future growth. Finding and analyzing advantages and disadvantages of various technologies for waste management will aid in the investigation of the best solution boundaries for an effective municipal solid waste management system, which is critical for future planning. Some of the challenges are:

- *Insufficient data:* The primary impediment to effective MSW system planning and design is a lack of sufficient information. Bin-filled level detail is unclear, although, for certain devices, trash weight is determined at the dumpsites via weight measuring instruments, however measurements at the source are unconfirmed. Designing and creating smart waste bins which can obtain physical status details like bin fill level volume, weight, and ambient condition for each bin on a regular basis are the challenges in resolving this issue. It usually necessitates the use of data acquisition systems such as a volumetric sensor, a humidity sensor, a load cell temperature sensor, and an ultrasonic sensor.
- *A* lack of details on the status of bins in real-time: Current MSW systems, in most cases, don't provide any operators with details on the status of bins in real-time. It is necessary to find a solution to this problem to properly plan the waste collection route. This situation calls for the installation of appropriate sensors to obtain real-time bin status data, and even a secure transmission network to transmit the information to a control station (Hannan et al., 2015).

- *A lack of coordination between the states and the federal government:* In this issue, there is a lack of cooperation between the national government and the states. States send necessary data late to the federal government, causing delays in implementing adequate ground-level actions. The lack of coordination with municipalities for the specific action plan, as well as poor strategic plans, is regarded as significant roadblocks.
- *Lack of awareness in public about waste segregation process:* It's indeed important that everyone is environmentally conscious and participates in waste separation. This is very important in managing municipal solid waste, and this would eventually lead to the best results. There seems to be an immediate need to educate the public about detrimental effects of improper segregation (a) by conducting events on municipal solid waste, (b) advertising about a strong awareness of the strengths of proper solid waste management, and (c) increasing interest from key stakeholders (Malav et al., 2020).

8 Conclusions

An effective solid waste management plan must include awareness, environmental friendliness, cost efficiency, and community satisfaction. The bounteous disposal of non-recyclable waste causes contamination of soil and water. This study addressed Waste to Energy alternatives for potential future applications. WtE option is acceptable as it provides environmentally sustainable alternatives while reducing reliance on conventional fuels. The advantages of proper waste management involve less greenhouse gas emissions, eliminating waste, earning money from energy sales, and reuse of waste. This paper highlights a variety of innovative strategies that have been identified in many countries for achieving smart and efficient waste management plans.

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References:

1. Abdullah, N., Alwesabi, O. A., & Abdullah, R. (2019). IoT-based smart waste management system in a smart city. In *Advances in Intelligent Systems and Computing* (Vol. 843). Springer International Publishing. https://doi.org/10.1007/978-3-319-99007-1_35
2. Abdel-Shafy, H. I., & Mansour, M. S. M. (2018). Solid waste issue: Sources, composition, disposal, recycling, and valorization. *Egyptian Journal of Petroleum*, *27*(4), 1275–1290. https://doi.org/10.1016/j.ejpe.2018.07.003
3. ADB. (2020). *Waste to Energy in the Age of the Circular Economy: Best Practice Handbook* (Issue November).
4. Adesra, A., Srivastava, V., Varjani, S., (2021). Valorization of Dairy Wastes: Integrative Approaches for Value Added Products. *Indian Journal of Microbiology*.

5. Agyeiwaah, E. (2020). The contribution of small accommodation enterprises to sustainable solid waste management. *Journal of Hospitality and Tourism Management*, *44*(November 2019), 1–9. https://doi.org/10.1016/j.jhtm.2020.04.013

6. Albrecht, R., Périssol, C., Ruaudel, F., Petit, J. Le, Terrom, G. (2010). Functional changes in culturable microbial communities during a co-composting process: Carbon source utilization and co-metabolism. *Waste Management*, *30*(5), 764–770. https://doi.org/10.1016/j.wasman.2009.12.008

7. Ali, T., Irfan, M., Alwadie, A. S., Glowacz, A. (2020). IoT-Based Smart Waste Bin Monitoring and Municipal Solid Waste Management System for Smart Cities. *Arabian Journal for Science and Engineering*, *45*(12), 10185–10198. https://doi.org/10.1007/s13369-020-04637-w

8. Alidoust, P., Keramati, M., Hamidian, P., Amlashi, A., Gharehveran, M. and Behnood, A., (2021). Prediction of the shear modulus of municipal solid waste (MSW): An application of machine learning techniques. *Journal of Cleaner Production*, 303, p.127053.

9. Azam, M., Jahromy, S. S., Raza, W., Raza, N., Lee, S. S., Kim, K. H., & Winter, F. (2020). Status, characterization, and potential utilization of municipal solid waste as renewable energy source: Lahore case study in Pakistan. *Environment International*, *134*(July 2019), 105291. https://doi.org/10.1016/j.envint.2019.105291

10. Aziz, S. Q., Omar, I. A., & Mustafa, J. S. (2018). Design and study for composting process site. *International Journal of Engineering Inventions*, *7*(9), 9–18.

11. Banerjee, P., Hazra, A., Ghosh, P., & Ganguly, A. (2019). Waste Management and Resource Efficiency. In *Waste Management and Resource Efficiency*. Springer Singapore. https://doi.org/10.1007/978-981-10-7290-1

12. Balachandar, R., Biruntha, M., Yuvaraj, A., Thangaraj, R., Subbaiya, R., Govarthanan, M., Kumar, P., & Karmegam, N. (2021). Earthworm intervened nutrient recovery and greener production of vermicompost from Ipomoea staphylina – An invasive weed with emerging environmental challenges. *Chemosphere*, *263*, 128080.

https://doi.org/10.1016/j.chemosphere.2020.128080

13. Bhat, R. A., Nazir, R., Ashraf, S., Ali, M., Bandh, S. A., & Kamili, A. N. (2014). Municipal solid waste generation rates and its management at Yusmarg forest ecosystem, a tourist resort in Kashmir. *Waste Management and Research*, *32*(2), 165–169. https://doi.org/10.1177/0734242X13518089

14. Bhat, R., Ahmad Dar, S., Ahmad Dar, D., & Hamid Dar, G. (2018). Municipal Solid Waste Generation and current Scenario of its Management in India. *International Journal of Advance Research in Science and Engineering*, *7*(2), 419–431. https://www.researchgate.net/publication/324756753_Municipal_Solid_Waste_Generation_and_current_Scenario_of_its_Management_in_India

15. Blasenbauer, D., Huber, F., Lederer, J., Quina, M. J., Blanc-Biscarat, D., Bogush, A., Bontempi, E., Blondeau, J., Chimenos, J. M., Dahlbo, H., Fagerqvist, J., Giro-Paloma, J., Hjelmar, O., Hyks, J., Keaney, J., Lupsea-Toader, M., O'Caollai, C. J., Orupõld, K., Pająk, T., … Fellner, J. (2020). Legal situation and current practice of waste incineration bottom ash utilisation in Europe. *Waste Management*, *102*, 868–883. https://doi.org/10.1016/j.wasman.2019.11.031

16. Bogomolov, A., Heßling, M., Wenzel, U., Princz, S., Hellmuth, T., Bernal, M. J. B., Sakharova, T., Usenov, I., Artyushenko, V., & Meyer, H. (2015). Development and testing of mid-infrared sensors for in-line process monitoring in biotechnology. *Sensors and Actuators, B: Chemical*, *221*, 1601–1610. https://doi.org/10.1016/j.snb.2015.07.118

17. Brunner, P. H., & Rechberger, H. (2015). Waste to energy - key element for sustainable waste management. *Waste Management*, *37*, 3–12. https://doi.org/10.1016/j.wasman.2014.02.003

18. Catarinucci, L., Colella, R., Consalvo, S., Patrono, L., Salvatore, A., and Sergi, I. (2019). IoT-oriented Waste Management System based on new RFID-Sensing Devices and Cloud Technologies. *2019 4th International Conference on Smart and Sustainable Technologies (SpliTech)*. doi:10.23919/splitech.2019.8783097.

19. Chand Malav, L., Yadav, K. K., Gupta, N., Kumar, S., Sharma, G. K., Krishnan, S., Rezania, S., Kamyab, H., Pham, Q. B., Yadav, S., Bhattacharyya, S., Yadav, V. K., & Bach, Q. V. (2020). A review on municipal solid waste as a renewable source for waste-to-energy project in India: Current practices, challenges, and future opportunities. *Journal of Cleaner Production*, *277*, 123227. https://doi.org/10.1016/j.jclepro.2020.123227

20. Cheng, J., Shi, F., Yi, J., & Fu, H. (2020). Analysis of the factors that affect the production of municipal solid waste in China. *Journal of Cleaner Production*, *259*, 120808.

21. Colvero, D. A., Gomes, A. P. D., Tarelho, L. A. da C., Matos, M. A. A. de, & Santos, K. A. dos. (2018). Use of a geographic information system to find areas for locating of municipal solid waste management facilities. *Waste Management*, *77*, 500–515. https://doi.org/10.1016/j.wasman.2018.04.036

22. da Costa, F. M., Daflon, S. D. A., Bila, D. M., da Fonseca, F. V., & Campos, J. C. (2018). Evaluation of the biodegradability and toxicity of landfill leachates after pretreatment using advanced oxidative processes. *Waste Management*, *76*, 606–613. https://doi.org/10.1016/j.wasman.2018.02.030

23. Das, S., Lee, S. H., Kumar, P., Kim, K. H., Lee, S. S., & Bhattacharya, S. S. (2019). Solid waste management: Scope and the challenge of sustainability. *Journal of Cleaner Production*, *228*. https://doi.org/10.1016/j.jclepro.2019.04.323

24. Elavarasan, S., Priya, A. K., & Kumar, V. K. (2020). Manufacturing fired clay brick using fly ash and M-Sand. *Materials Today: Proceedings*, *37*(Part 2), 872–876. https://doi.org/10.1016/j.matpr.2020.06.042

25. Fan, Y. Van, Klemeš, J. J., Lee, C. T., & Perry, S. (2018). Anaerobic digestion of municipal solid waste: Energy and carbon emission footprint. *Journal of Environmental Management*, *223*(June), 888–897. https://doi.org/10.1016/j.jenvman.2018.07.005

26. Fang, Y., Paul, M.C., Varjani, S., Li, X., Park, Y.K., You, S. (2021). Concentrated solar thermochemical gasification of biomass: Principles, applications, and development,

Renewable & Sustainable Energy Reviews, 150, 111484 (Doi: https://doi.org/10.1016/j.rser.2021.111484)

27. Flesoura, G., Dilissen, N., Dimitrakis, G., Vleugels, J., & Pontikes, Y. (2021). A new approach for the vitrification of municipal solid waste incinerator bottom ash by microwave irradiation. *Journal of Cleaner Production*, *284*(xxxx), 124787. https://doi.org/10.1016/j.jclepro.2020.124787
28. Fernández-González, L., Calvete, E., & Orue, I. (2017). Mujeres víctimas de violencia de género en centros de acogida: características sociodemográficas y del maltrato. *Psychosocial Intervention*, *26*(1), 9–17. https://doi.org/10.1016/j.psi.2016.10.001
29. Gallardo, A., Carlos, M., Peris, M., & Colomer, F. J. (2015). Methodology to design a municipal solid waste pre-collection system. A case study. *Waste Management*, *36*, 1–11.
30. Ghosh, S., Narjinary, M., Sen, A., Bandyopadhyay, R., & Roy, S. (2014). Fast detection of low concentration carbon monoxide using calcium-loaded tin oxide sensors. *Sensors and Actuators, B: Chemical*, *203*, 490–496. https://doi.org/10.1016/j.snb.2014.06.111
31. Głąb, T., Żabiński, A., Sadowska, U., Gondek, K., Kopeć, M., Mierzwa-Hersztek, M., Tabor, S., & Stanek-Tarkowska, J. (2020). Fertilization effects of compost produced from maize, sewage sludge and biochar on soil water retention and chemical properties. *Soil and Tillage Research*, *197*(October 2019). https://doi.org/10.1016/j.still.2019.104493
32. Grytnes, R. (2018). A Sense of Security: Carpentry Apprentices Handling Uncertain and Dangerous Work Tasks. *Ethnos*, *83*(2), 353–370. https://doi.org/10.1080/00141844.2017.1282972
33. Gupta, N., Yadav, K. K., & Kumar, V. (2015). A review on current status of municipal solid waste management in India. *Journal of Environmental Sciences*, *37*, 206–217.
34. Guran, S. (2018). Sustainable waste-to-energy technologies: Gasification and pyrolysis. In *Sustainable Food Waste-to-Energy Systems* (Issue Chapter 9). Elsevier Inc.

https://doi.org/10.1016/B978-0-12-811157-4.00008-5

35. Hannan, M. A., Hossain Lipu, M. S., Akhtar, M., Begum, R. A., Al Mamun, M. A., Hussain, A., Mia, M. S., & Basri, H. (2020). Solid waste collection optimization objectives, constraints, modeling approaches, and their challenges toward achieving sustainable development goals. *Journal of Cleaner Production*, *277*, 123557. https://doi.org/10.1016/j.jclepro.2020.123557

36. Hannan, M. A., Abdulla Al Mamun, M., Hussain, A., Basri, H., & Begum, R. A. (2015). A review on technologies and their usage in solid waste monitoring and management systems: Issues and challenges. *Waste Management*, *43*, 509–523. https://doi.org/10.1016/j.wasman.2015.05.033

37. Hannan, M. A., Arebey, M., Begum, R. A., & Basri, H. (2011). Radio Frequency Identification (RFID) and communication technologies for solid waste bin and truck monitoring system. *Waste Management*, *31*(12), 2406–2413. https://doi.org/10.1016/j.wasman.2011.07.022

38. Hameed, Z., Aslam, M., Khan, Z., Maqsood, K., Atabani, A. E., Ghauri, M., Khurram, M. S., Rehan, M., & Nizami, A. S. (2021). Gasification of municipal solid waste blends with biomass for energy production and resources recovery: Current status, hybrid technologies and innovative prospects. *Renewable and Sustainable Energy Reviews*, *136*(March 2020), 110375. https://doi.org/10.1016/j.rser.2020.110375

39. Harris-Lovett, S., Lienert, J., & Sedlak, D. (2019). A mixed-methods approach to strategic planning for multi-benefit regional water infrastructure. *Journal of Environmental Management*, *233*, 218–237.

40. Hietala, M., Varrio, K., Berglund, L., Soini, J., & Oksman, K. (2018). Potential of municipal solid waste paper as raw material for production of cellulose nanofibres. *Waste Management*, *80*, 319–326. https://doi.org/10.1016/j.wasman.2018.09.033

41. Ho, M. C., Ong, V. Z., & Wu, T. Y. (2019). Potential use of alkaline hydrogen peroxide in lignocellulosic biomass pretreatment and valorization – A review. *Renewable and Sustainable Energy Reviews*, *112*(April), 75–86.

https://doi.org/10.1016/j.rser.2019.04.082

42. Huang, J., Pham, D. T., Ji, C., Wang, Z., & Zhou, Z. (2019). Multi-parameter dynamical measuring system using fibre Bragg grating sensors for industrial hydraulic piping. *Measurement: Journal of the International Measurement Confederation*, *134*, 226–235. https://doi.org/10.1016/j.measurement.2018.10.069
43. Ibrahimoglu, B., Cucen, A., & Yilmazoglu, M. Z. (2017). Numerical modeling of a downdraft plasma gasification reactor. *International Journal of Hydrogen Energy*, *42*(4), 2583–2591.
44. IEA bioenergy (2019) Available at- https://www.ieabioenergy.com/wp-content/uploads/2013/10/40_IEAPositionPaperMSW.pdf (Last accessed: 20.08.2021)
45. Istrate, I.-R., Iribarren, D., Gálvez-Martos, J.-L., & Dufour, J. (2020). Review of life-cycle environmental consequences of waste-to-energy solutions on the municipal solid waste management system. *Resources, Conservation and Recycling*, *157*, 104778.
46. Jahnavi, N., Kanmani, K., Kumar, P. S., & Varjani, S. (2020). *Conversion of waste plastics into low emissive hydrocarbon fuel using catalyst produced from biowaste. Environmental Science and Pollution Research.* doi:10.1007/s11356-020-11398-4
47. Jain, M. S., Paul, S., & Kalamdhad, A. S. (2020). Kinetics and physics during composting of various organic wastes: Statistical approach to interpret compost application feasibility. *Journal of Cleaner Production*, *255*, 120324. https://doi.org/10.1016/j.jclepro.2020.120324
48. Joseph, L. P., & Prasad, R. (2020). Assessing the sustainable municipal solid waste (MSW) to electricity generation potentials in selected Pacific Small Island Developing States (PSIDS). *Journal of Cleaner Production*, *248*, 119222. https://doi.org/10.1016/j.jclepro.2019.119222
49. Jung, J., Han, S. U., & Kim, B. (2019). Digital numerical map-oriented estimation of solar energy potential for site selection of photovoltaic solar panels on national highway slopes. *Applied Energy*, *242*(February), 57–68. https://doi.org/10.1016/j.apenergy.2019.03.101

50. Khanal, S., Varjani, S., Sze Ki Lin, C. and Awasthi, M., (2020). Waste-to-resources: Opportunities and challenges. *Bioresource Technology*, 317, p.123987.

51. Kiyasudeen, K., Ibrahim, M. H., Quaik, S., & Ismail, S. A. (2016). An introduction to anaerobic digestion of organic wastes. In *Prospects of organic waste management and the significance of earthworms* (pp. 23–44). Springer.

52. Kubra Isgor, P., Marcali, M., Keser, M., & Elbuken, C. (2015). Microfluidic droplet content detection using integrated capacitive sensors. *Sensors and Actuators, B: Chemical*, *210*, 669–675. https://doi.org/10.1016/j.snb.2015.01.018

53. Kumar, A., & Samadder, S. R. (2017). A review on technological options of waste to energy for effective management of municipal solid waste. *Waste Management*, *69*, 407–422. https://doi.org/10.1016/j.wasman.2017.08.046

54. Kumar, R., Singh, R., Hui, D., Feo, L., & Fraternali, F. (2018). Graphene as biomedical sensing element: State of art review and potential engineering applications. *Composites Part B: Engineering*, *134*, 193–206. https://doi.org/10.1016/j.compositesb.2017.09.049

55. Liang, J., Luo, L., Li, D., Varjani, S., Xu, Y., Wong, J.W.C. 2021. Promoting anaerobic co-digestion of sewage sludge and food waste with different types of conductive materials: Performance, stability, and underlying mechanism. Bioresource Technology, 337, 125278 (Doi: https://doi.org/10.1016/j.biortech.2021.125384)

56. Logan, M., & Visvanathan, C. (2019). Management strategies for anaerobic digestate of organic fraction of municipal solid waste: Current status and future prospects. *Waste Management and Research*, *37*(1_suppl), 27–39. https://doi.org/10.1177/0734242X18816793

57. Lu, J. W., Chang, N. Bin, & Liao, L. (2013). Environmental informatics for solid and hazardous waste management: Advances, challenges, and perspectives. *Critical Reviews in Environmental Science and Technology*, *43*(15), 1557–1656. https://doi.org/10.1080/10643389.2012.671097

58. Luo, L., Kaur, G., Zhao, J., Zhou, J., Xu, S, Varjani, S., Wong, J.W.C. (2021). Optimization of water replacement during leachate recirculation for two-phase food

waste anaerobic digestion system with off-gas diversion. *Bioresource Technology*, 335, 125234

59. Mahmudul, H. M., Rasul, M. G., Akbar, D., Narayanan, R., & Mofijur, M. (2021). A comprehensive review of the recent development and challenges of a solar-assisted biodigester system. Science of the Total Environment, 753. https://doi.org/10.1016/j.scitotenv.2020.141920

60. Makarichi, L., Jutidamrongphan, W., & Techato, K. anan. (2018). The evolution of waste-to-energy incineration: A review. *Renewable and Sustainable Energy Reviews*, *91*(May 2017), 812–821. https://doi.org/10.1016/j.rser.2018.04.088

61. Mamun, M. A. Al, Hannan, M. A., Hussain, A., & Basri, H. (2016). Theoretical model and implementation of a real time intelligent bin status monitoring system using rule based decision algorithms. *Expert Systems with Applications*, *48*, 76–88. https://doi.org/10.1016/j.eswa.2015.11.025

62. Manu, M., Li, D., Liwen, L., Jun, Z., Varjani, S. and Wong, J., (2021). A review on nitrogen dynamics and mitigation strategies of food waste digestate composting. *Bioresource Technology*, 334, p.125032.

63. Markl, E., and Lackner, M. (2020). Devulcanization Technologies for Recycling of Tire-Derived Rubber: A Review. *Materials* 13, 1246. doi:10.3390/ma13051246.

64. Materazzi, M., & Foscolo, P. U. (2019). The role of waste and renewable gas to decarbonize the energy sector. In *Substitute Natural Gas from Waste* (pp. 1–19). Elsevier.

65. McLeod, F., Erdogan, G., Cherrett, T., Bektas, T., Davies, N., Speed, C., Dickinson, J., & Norgate, S. (2013). Dynamic collection scheduling using remote asset monitoring. *Transportation Research Record*, *2378*, 65–72. https://doi.org/10.3141/2378-07

66. Mdukaza, S., Isong, B., Dladlu, N., and Abu-Mahfouz, A. (2018). Analysis of IoT-Enabled Solutions in Smart Waste Management. *IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*. doi:10.1109/iecon.2018.8591236.

67. Mengistu, T., Gebrekidan, H., Kibret, K., Woldetsadik, K., Shimelis, B., & Yadav, H. (2018). Comparative effectiveness of different composting methods on the stabilization, maturation and sanitization of municipal organic solid wastes and dried faecal sludge mixtures. *Environmental Systems Research*, *6*(1). https://doi.org/10.1186/s40068-017-0079-4

68. Michalec, M., & Tymecki, Ł. (2018). 3D printed flow-through cuvette insert for UV–Vis spectrophotometric and fluorescence measurements. *Talanta*, *190*, 423–428. https://doi.org/10.1016/j.talanta.2018.08.026

69. Mishra, B., Varjani, S., Agarwal, D.C., Mandal, S.K., Ngo, H.H., Taherzadeh, M.J., Chang, J.S., You, S., Guo, W., 2020. Engineering biocatalytic material for the remediation of pollutants: A comprehensive review. Environmental Technology & Innovation, 20, 101063 (Doi: https://doi.org/10.1016/j.eti.2020.101063)

70. Mittal, S., Pathak, M., Shukla, P. R., & Ahlgren, E. (2017). GHG mitigation & sustainability co-benefits of urban solid waste management strategies: A case study of Ahmedabad, India. *Chemical Engineering Transactions*, *56*(January), 457–462. https://doi.org/10.3303/CET1756077

71. Mohammadi, M., Jämsä-Jounela, S. L., & Harjunkoski, I. (2019). Optimal planning of municipal solid waste management systems in an integrated supply chain network. *Computers and Chemical Engineering*, *123*, 155–169. https://doi.org/10.1016/j.compchemeng.2018.12.022

72. Mohanty, S. S., Koul, Y., Varjani, S., Pandey, A., Ngo, H. H., Chang, J.-S., et al. (2021). A critical review on various feedstocks as sustainable substrates for biosurfactants production: a way towards cleaner production. *Microb. Cell Fact.* 20, 1–13.

73. Moustakas, K., Loizidou, M., Rehan, M., & Nizami, A. S. (2020). A review of recent developments in renewable and sustainable energy systems: Key challenges and future perspective. *Renewable and Sustainable Energy Reviews*, *119*(xxxx). https://doi.org/10.1016/j.rser.2019.109418

74. Moya, D., Aldás, C., López, G., & Kaparaju, P. (2017). Municipal solid waste as a valuable renewable energy resource: a worldwide opportunity of energy recovery by using Waste-To-Energy Technologies. *Energy Procedia*, *134*, 286–295.

75. Mukherjee, C., Denney, J., Mbonimpa, E. G., Slagley, J., & Bhowmik, R. (2020). A review on municipal solid waste-to-energy trends in the USA. *Renewable and Sustainable Energy Reviews*, *119*(March 2019), 109512. https://doi.org/10.1016/j.rser.2019.109512

76. Nivetha, M., Priyadharshini, P., & Swetha, J. R. (2019). *Identification and Analysis of Foot Ulceration Using Load Cell Technique*.

77. Ong, H. C., Milano, J., Silitonga, A. S., Hassan, M. H., Shamsuddin, A. H., Wang, C. T., Indra Mahlia, T. M., Siswantoro, J., Kusumo, F., & Sutrisno, J. (2019). Biodiesel production from Calophyllum inophyllum-Ceiba pentandra oil mixture: Optimization and characterization. *Journal of Cleaner Production*, *219*, 183–198. https://doi.org/10.1016/j.jclepro.2019.02.048

78. Pan, H., Lei, H., Liu, X., Wei, H., & Liu, S. (2017). Assessment on the leakage hazard of landfill leachate using three-dimensional excitation-emission fluorescence and parallel factor analysis method. *Waste Management*, *67*, 214–221. https://doi.org/10.1016/j.wasman.2017.05.041

79. Pandey, A.K., Gaur, V.K., Udayan, A., Varjani, S., Kim, S.H., & Wong, J.W.C., (2021). Biocatalytic remediation of industrial pollutants for environmental sustainability: Research needs and opportunities. *Chemoshpere*, 272, 129936

80. Pappalardo, G., Selvaggi, R., Bracco, S., Chinnici, G., & Pecorino, B. (2018). Factors affecting purchasing process of digestate: evidence from an economic experiment on Sicilian farmers' willingness to pay. *Agricultural and Food Economics*, *6*(1). https://doi.org/10.1186/s40100-018-0111-7

81. Paritosh, K., Yadav, M., Mathur, S., Balan, V., Liao, W., Pareek, N., and Vivekanand, V. (2018). Organic Fraction of Municipal Solid Waste: Overview of Treatment Methodologies to Enhance Anaerobic Biodegradability. *Frontiers in Energy*

Research 6. doi:10.3389/fenrg.2018.00075.

82. Parthiba Karthikeyan, O., Trably, E., Mehariya, S., Bernet, N., Wong, J. W. C., & Carrere, H. (2018). Pretreatment of food waste for methane and hydrogen recovery: A review. *Bioresource Technology*, *249*, 1025–1039. https://doi.org/10.1016/j.biortech.2017.09.105

83. Pasalari, H., Farzadkia, M., Gholami, M., & Emamjomeh, M. M. (2018). *Management of landfill leachate in Iran: valorization, characteristics, and environmental approaches. Environmental Chemistry Letters.* doi:10.1007/s10311-018-0804-x

84. Patil, B. S., Agnes Anto, C., & Singh, D. N. (2017). Simulation of municipal solid waste degradation in aerobic and anaerobic bioreactor landfills. *Waste Management and Research*, *35*(3), 301–312. https://doi.org/10.1177/0734242X16679258

85. Pergola, M., Persiani, A., Palese, A. M., Di Meo, V., Pastore, V., D'Adamo, C., & Celano, G. (2018). Composting: The way for a sustainable agriculture. *Applied Soil Ecology*, *123*, 744–750.

86. Prajapati, P., Varjani, S., Singhania, R..R., Patel, A.K., Awasthi, M.K., Sindhu, R., Zhang, Z., Binod, P., Awasthi, S.K., Chaturvedi, P., 2021. Critical Review on Technological Advancements for Effective Waste Management of Municipal Solid Waste - Updates and Way Forward, Environmental Technology & Innovation, 23, 101749 (Doi: https://doi.org/10.1016/j.eti.2021.101749)

87. Pujara, Y., Pathak, P., Sharma, A., & Govani, J. (2019). Review on Indian Municipal Solid Waste Management practices for reduction of environmental impacts to achieve sustainable development goals. *Journal of Environmental Management*, *248*(July), 109238. https://doi.org/10.1016/j.jenvman.2019.07.009

88. Putro, F. A., Pranolo, S. H., Waluyo, J., & Setyawan, A. (2020). Thermodynamic study of palm kernel shell gasification for aggregate heating in an asphalt mixing plant. *International Journal of Renewable Energy Development*, *9*(2), 311–317. https://doi.org/10.14710/ijred.9.2.311-317

89. Rajcoomar, A., & Ramjeawon, T. (2017). Life cycle assessment of municipal solid

waste management scenarios on the small island of Mauritius. *Waste Management & Research*, *35*(3), 313–324.

90. Rajmohan KS, Ramya C and Varjani S (2019). Trends and advances in bioenergy production and sustainable solid waste management, *Energy and Environment* 1-27 (Doi: 10.1177/095830505X19882415)

91. Rajput, R., Prasad, G., & A.K., C. (2009). Scenario of solid waste management in present Indian context. *Caspian Journal of Environmental Sciences*, *7*(1), 45–53.

92. Ramachandra, T. V., Bharath, H. A., Kulkarni, G., & Han, S. S. (2018). Municipal solid waste: Generation, composition and GHG emissions in Bangalore, India. *Renewable and Sustainable Energy Reviews*, *82*(June 2017), 1122–1136. https://doi.org/10.1016/j.rser.2017.09.085

93. Rana, R., Ganguly, R., & Gupta, A. K. (2019). Life-cycle assessment of municipal solid-waste management strategies in Tricity region of India. *Journal of Material Cycles and Waste Management*, *21*(3), 606–623. https://doi.org/10.1007/s10163-018-00822-0

94. Rastogi, M., Nandal, M., & Khosla, B. (2020). Microbes as vital additives for solid waste composting. *Heliyon*, *6*(2), e03343. https://doi.org/10.1016/j.heliyon.2020.e03343

95. Rathore, P., Sarmah, S. P., & Singh, A. (2020). Location–allocation of bins in urban solid waste management: a case study of Bilaspur city, India. *Environment, Development and Sustainability*, *22*(4), 3309–3331. https://doi.org/10.1007/s10668-019-00347-y

96. Rene, E. R., Ge, J., Kumar, G., Singh, R. P., & Varjani, S. (2020). *Resource recovery from wastewater, solid waste, and waste gas: engineering and management aspects. Environmental Science and Pollution Research.* doi:10.1007/s11356-020-08802-4

97. Ramos, A., Berzosa, J., Espí, J., Clarens, F., & Rouboa, A. (2020). Life cycle costing for plasma gasification of municipal solid waste: A socio-economic approach. *Energy Conversion and Management*, *209*(January), 112508.

https://doi.org/10.1016/j.enconman.2020.112508

98. Saja, A., Zimar, A., and Junaideen, S. (2021). Municipal Solid Waste Management Practices and Challenges in the Southeastern Coastal Cities of Sri Lanka. *Sustainability* 13, 4556. doi:10.3390/su13084556.

99. Sakurama, K., Kosaka, Y., & Nishida, S. ichiro. (2018). Formation Control of Swarm Robots with Multiple Proximity Distance Sensors. *International Journal of Control, Automation and Systems*, *16*(1), 16–26. https://doi.org/10.1007/s12555-016-0741-z

100. Scarlat, N., Motola, V., Dallemand, J. F., Monforti-Ferrario, F., & Mofor, L. (2015). Evaluation of energy potential of Municipal Solid Waste from African urban areas. *Renewable and Sustainable Energy Reviews*, *50*, 1269–1286. https://doi.org/10.1016/j.rser.2015.05.067

101. Scarlat, N., Fahl, F., & Dallemand, J.-F. (2019). Status and opportunities for energy recovery from municipal solid waste in Europe. *Waste and Biomass Valorization*, *10*(9), 2425–2444.

102. Scherzinger, M., & Kaltschmitt, M. (2021). Thermal pre-treatment options to enhance anaerobic digestibility – A review. *Renewable and Sustainable Energy Reviews*, *137*(December 2020), 110627. https://doi.org/10.1016/j.rser.2020.110627

103. Sekar, M., Mathimani, T., Alagumalai, A., Chi, N. T. L., Duc, P. A., Bhatia, S. K., Brindhadevi, K., & Pugazhendhi, A. (2021). A review on the pyrolysis of algal biomass for biochar and bio-oil – Bottlenecks and scope. *Fuel*, *283*(September 2020), 119190. https://doi.org/10.1016/j.fuel.2020.119190

104. Shah AV, Srivastava VK , Mohanty SS & Varjani S, Municipal solid waste as a sustainable resource for energy production: State-of-the-art review. Journal of Environmental Chemical Engineering, (2021)

105. Sharma, A., Ganguly, R. and Gupta, A., (2018) Matrix method for evaluation of existing solid waste management system in Himachal Pradesh, India. *Journal of Material Cycles and Waste Management*, 20(3), pp.1813-1831.

106. Sharma, B. K., & Chandel, M. K. (2017). Life cycle assessment of potential municipal

solid waste management strategies for Mumbai, India. *Waste Management & Research*, *35*(1), 79–91.

107. Sharma, K. and Jain, S., (2019). Overview of Municipal Solid Waste Generation, Composition, and Management in India. *Journal of Environmental Engineering*, 145(3), p.04018143.

108. Singh, A. (2019). Remote sensing and GIS applications for municipal waste management. *Journal of Environmental Management* 243, 22-29. doi:10.1016/j.jenvman.2019.05.017.

109. Sienkiewicz, M., Janik, H., Borzędowska-Labuda, K., & Kucińska-Lipka, J. (2017). Environmentally friendly polymer-rubber composites obtained from waste tyres: A review. *Journal of Cleaner Production*, *147*, 560–571. https://doi.org/10.1016/j.jclepro.2017.01.121

110. Singh, A. (2019). Remote sensing and GIS applications for municipal waste management. *Journal of Environmental Management*, *243*(May), 22–29. https://doi.org/10.1016/j.jenvman.2019.05.017

111. Sipra, A. T., Gao, N., & Sarwar, H. (2018). Municipal solid waste (MSW) pyrolysis for bio-fuel production: A review of effects of MSW components and catalysts. *Fuel Processing Technology*, *175*, 131–147.

112. Somers, M. H., Azman, S., Sigurnjak, I., Ghyselbrecht, K., Meers, E., Meesschaert, B., & Appels, L. (2018). Effect of digestate disintegration on anaerobic digestion of organic waste. *Bioresource Technology*, *268*, 568–576. https://doi.org/10.1016/j.biortech.2018.08.036

113. Song, B., Lin, R., Lam, C. H., Wu, H., Tsui, T. H., & Yu, Y. (2021). Recent advances and challenges of inter-disciplinary biomass valorization by integrating hydrothermal and biological techniques. *Renewable and Sustainable Energy Reviews*, *135*(September 2020), 110370. https://doi.org/10.1016/j.rser.2020.110370

114. Soobhany, N., Mohee, R., & Garg, V. K. (2017). Inactivation of bacterial pathogenic load in compost against vermicompost of organic solid waste aiming to achieve

sanitation goals: A review. *Waste Management*, *64*, 51–62. https://doi.org/10.1016/j.wasman.2017.03.003

115. Srivastava, V., Goel, G., Thakur, V. K., Singh, R. P., Ferreira de Araujo, A. S., & Singh, P. (2020). Analysis and advanced characterization of municipal solid waste vermicompost maturity for a green environment. *Journal of Environmental Management*, *255*(July 2019), 109914. https://doi.org/10.1016/j.jenvman.2019.109914

116. Tabular Data (2021). *Sulabhenvis.nic.in*. Available at: http://www.sulabhenvis.nic.in/Database/TabularData_9639.aspx [Accessed August 1, 2021].

117. Thomas, P., & Soren, N. (2020). An overview of municipal solid waste-to-energy application in Indian scenario. *Environment, Development and Sustainability*, *22*(2), 575–592.

118. Tripathi, K. M., Sachan, A., Castro, M., Choudhary, V., Sonkar, S. K., & Feller, J. F. (2018). Green carbon nanostructured quantum resistive sensors to detect volatile biomarkers. *Sustainable Materials and Technologies*, *16*(2017), 1–11. https://doi.org/10.1016/j.susmat.2018.01.001

119. Tsukiji, M., Gamaralalage, P., Pratomo, I., Onogawa, K., Alverson, K., Honda, S., Ternald, D., Dilley, M., Fujioka, J., and Condrorini, D. (2021). *Waste Management during the COVID-19 Pandemic From Response to Recovery*. Availaible at- https://wedocs.unep.org/bitstream/handle/20.500.11822/33416/WMC-19.pdf?sequence=1&isAllowed=y

120. Tyagi, V. K., Fdez-Güelfo, L. A., Zhou, Y., Álvarez-Gallego, C. J., Garcia, L. I. R., & Ng, W. J. (2018). Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): Progress and challenges. *Renewable and Sustainable Energy Reviews*, *93*(June 2017), 380–399. https://doi.org/10.1016/j.rser.2018.05.051

121. Uzoejinwa, B. B., He, X., Wang, S., El-Fatah Abomohra, A., Hu, Y., & Wang, Q. (2018). Co-pyrolysis of biomass and waste plastics as a thermochemical conversion technology for high-grade biofuel production: Recent progress and future directions

elsewhere worldwide. *Energy Conversion and Management*, *163*(January), 468–492. https://doi.org/10.1016/j.enconman.2018.02.004

122. Usmani, Z., Kumar, V., Varjani, S., Gupta, P., Rani, R., & Chandra, A. (2020). Municipal solid waste to clean energy system: A contribution toward sustainable development. In *Current Developments in Biotechnology and Bioengineering: Resource Recovery from Wastes* (Issue 1). Elsevier. https://doi.org/10.1016/B978-0-444-64321-6.00011-2.

123. Varjani, S.J., 2017. Microbial degradation of petroleum hydrocarbons. Bioresource Technology, 223, 277-286.

124. Varjani, S.J., Gnansounou, E., Pandey, A., 2017. Comprehensive review on toxicity of persistent organic pollutants from petroleum refinery waste and their degradation by microorganisms. Chemosphere, 188, 280-291.

125. Varjani, S.J., Upasani, V.N., 2016. Biodegradation of petroleum hydrocarbons by oleophilic strain of *Pseudomonas aeruginosa* NCIM 5514, Bioresource Technology, 222, 195-201.

126. Varjani, S., Rakholiya, P., Shindhal, T., Shah, A.V., Ngo, H.H.. 2021a. Trends in dye industry effluent treatment and recovery of value added products. Journal of Water Process Engineering, 39, 101734 (Doi: https://doi.org/10.1016/j.jwpe.2020.101734)

127. Varjani, S., Shah, A.V., Vyas, S. & Srivastava V.K. 2021b. Processes and Prospects on Valorizing Solid Waste for the production of Valuable Products Employing Bio-routes: A systematic review, Chemosphere, 282, 130954 (Doi: https://doi.org/10.1016/j.chemosphere.2021.130954).

128. Varjani, S., Upasani, V.N., 2021. Bioaugmentation of *Pseudomonas aeruginosa* NCIM 5514 - A novel oily waste degrader for treatment of petroleum hydrocarbons. Bioresource Technology, 319, 124240 (Doi: https://doi.org/10.1016/j.biortech.2020.124240).

129. Varjani, S., Upasani, V.N., Pandey, A., (2020). Bioremediation of oily sludge polluted soil employing a novel strain of Pseudomonas aeruginosa and phytotoxicity of

petroleum hydrocarbons for seed germination. Science of The Total Environment, 737, 139766 (Doi: 10.1016/j.scitotenv.2020.139766).

130. Vaish, B., Sharma, B., Srivastava, V., Singh, P., Ibrahim, M. H., Singh, R. P. (2019). Energy recovery potential and environmental impact of gasification for municipal solid waste. *Biofuels*, *10*(1), 87–100. https://doi.org/10.1080/17597269.2017.1368061

131. Velghe, I., Carleer, R., Yperman, J.,Schreurs, S. (2011). *Study of the pyrolysis of municipal solid waste for the production of valuable products. Journal of Analytical and Applied Pyrolysis, 92(2), 366–375.* doi:10.1016/j.jaap.2011.07.011

132. Venkata Mohan, S., Varjani, S., Pant, D., Sauer, M., Chang, J., (2020). Circular bioeconomy approaches for sustainability. *Bioresource Technology*, 318, 124084 (Doi: https://doi.org/10.1016/j.biortech.2020.124084)

133. Vicentini, F., Giusti, A., Rovetta, A., Fan, X., He, Q., Zhu, M., & Liu, B. (2009). Sensorized waste collection container for content estimation and collection optimization. *Waste Management*, *29*(5), 1467–1472. https://doi.org/10.1016/j.wasman.2008.10.017

134. Vigneswaran, S., Kandasamy, J., & Johir, M. A. H. (2016). Sustainable Operation of Composting in Solid Waste Management. *Procedia Environmental Sciences*, *35*, 408–415. https://doi.org/10.1016/j.proenv.2016.07.022

135. Vrancken, C., Longhurst, P. J., & Wagland, S. T. (2017). Critical review of real-time methods for solid waste characterisation: Informing material recovery and fuel production. *Waste Management*, *61*, 40–57. https://doi.org/10.1016/j.wasman.2017.01.019

136. Wang, Y., Zhang, X., Liao, W., Wu, J., Yang, X., Shui, W., Deng, S., Zhang, Y., Lin, L., & Xiao, Y. (2018). Investigating impact of waste reuse on the sustainability of municipal solid waste (MSW) incineration industry using emergy approach: A case study from Sichuan province, China. *Waste Management*, *77*, 252–267.

137. Waste incineration & public health (2000). Washington, D.C.: National Academy Press.

138. Wong, S. (2020). Solid waste in China-Statistics & facts. https://www.statista.com/topics/5655/solid-waste-in-china/

139. Wu, R., Zhang, S., Zhang, Q., Liu, C., Tian, G., & Lv, J. (2019). Volumetric hydrogel sensor enables visual and quantitative detection of sulfion. *Sensors and Actuators, B: Chemical*, *282*(November 2018), 750–755. https://doi.org/10.1016/j.snb.2018.10.117

140. Xue, W., Hu, X., Wei, Z., Mei, X., Chen, X., & Xu, Y. (2019). A fast and easy method for predicting agricultural waste compost maturity by image-based deep learning. *Bioresource Technology*, *290*(July), 121761. https://doi.org/10.1016/j.biortech.2019.121761

141. Yaashikaa PR, Kumar PS, Saravanan A, Varjani S and Ramamurthy R (2020), Bioconversion of municipal solid waste into bio-based products: A review on valorisation and sustainable approach for circular bioeconomy. *Science of The Total Environment,* 748, 141312

142. Yan, X., Li, H., & Su, X. (2018). Review of optical sensors for pesticides. *TrAC - Trends in Analytical Chemistry*, *103*, 1–20. https://doi.org/10.1016/j.trac.2018.03.004

143. Yap, H. Y., & Nixon, J. D. (2015). A multi-criteria analysis of options for energy recovery from municipal solid waste in India and the UK. *Waste Management*, *46*, 265–277. https://doi.org/10.1016/j.wasman.2015.08.002

144. Yogalakshmi, K.N., Devi, T.P., Sivashanmugam, P., Kavitha, S., Kannah, Y.R., Varjani, S., Kumar, A.S., Kumar, G., Banu, R.J. 2022. Lignocellulosic biomass-based pyrolysis: A comprehensive review. Chemosphere, 286, 131824 (Doi: https://doi.org/10.1016/j.chemosphere.2021.131824)

145. Yuvaraj, A., Thangaraj, R., Ravindran, B., Chang, S. W., & Karmegam, N. (2021). Centrality of cattle solid wastes in vermicomposting technology – A cleaner resource recovery and biowaste recycling option for agricultural and environmental sustainability. *Environmental Pollution*, *268*, 115688. https://doi.org/10.1016/j.envpol.2020.115688

146. Zamri, M. F. M. A., Hasmady, S., Akhiar, A., Ideris, F., Shamsuddin, A. H., Mofijur,

M., Fattah, I. M. R., & Mahlia, T. M. I. (2021). A comprehensive review on anaerobic digestion of organic fraction of municipal solid waste. *Renewable and Sustainable Energy Reviews*, *137*(November 2020), 110637. https://doi.org/10.1016/j.rser.2020.110637

147. Zhang, Y., Xiang, J., Wang, Y., Qiao, Z., & Wang, W. (2019). A 3D printed centrifugal microfluidic platform for spilled oil enrichment and detection based on solid phase extraction (SPE). *Sensors and Actuators, B: Chemical*, *296*(May), 126603. https://doi.org/10.1016/j.snb.2019.05.080

148. Zhu, Y., Zhang, Y., Luo, D., Chong, Z., Li, E., and Kong, X. (2020). A review of municipal solid waste in China: characteristics, compositions, influential factors and treatment technologies. *Environ. Dev. Sustain.*, 1–20.

149. Zorpas, A. A. (2020). Strategy development in the framework of waste management. *Science of the Total Environment*, *716*, 137088. https://doi.org/10.1016/j.scitotenv.2020.137088

150. Zsigraiova, Z., Semiao, V., & Beijoco, F. (2013). Operation costs and pollutant emissions reduction by definition of new collection scheduling and optimization of MSW collection routes using GIS. The case study of Barreiro, Portugal. *Waste Management*, *33*(4), 793–806. https://doi.org/10.1016/j.wasman.2012.11.015

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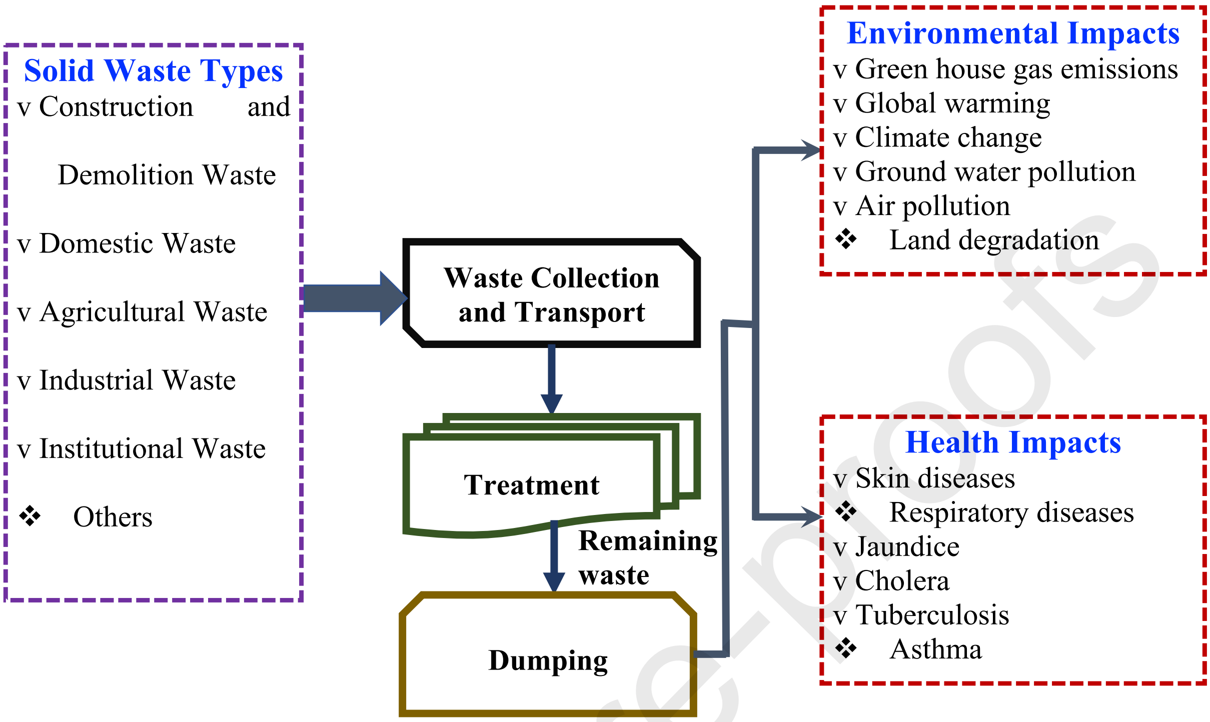

Figure 1: Schematic Diagram on Environmental and Health Impacts of Dumped Solid Wastes

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Table 1: Municipal solid waste generation and management at global scale

Country	Solid waste generation (MT/D)	Treatment process	Capacity of electricity generation (MW)
USA	6,24,700	Landfilling, Recycling, Resource Recovery, WtE, Composting, MBT, AD	2254
China	5,20,548	Incineration, Pyrolysis, Conventional gasification, Plasma Arc Gasification, Composting	-
Brazil	1,49,096	Recycling, Resource recovery, Sanitary Landfilling, Composting, Incineration	-
Japan	1,44,466	WtE, Recycling, Resource Recovery, Recover electricity and fuel from biomass, Landfilling	1501
India	1,09,589	Composting, Vermicomposting, WtE, Landfilling, Biogas, RDF/Pelletization, Bioreactor Landfilling	274
Germany	1,27,816	WtE, Recycling, Composting	1888

Russia	1,00,027	Recycling, AD, Composting, Resource recovery, MBT, Incineration, Landfilling, WtE	-
Sweden	12,329	WtE, Recycling, Landfilling, Composting	459
Spain	72,137	Landfilling, Recycling, Composting	251
South Korea	48,397	Recycling	184
Thailand	39,452	Recycling	75
Singapore	7205	WtE, Recycling	128
UK	97,342	Recycling, Resource recovery, AD, MBT, Composting, Incineration, Landfilling	781
South Africa	53,425	Recycling, Disposal, Incineration	-
Switzerland	14,329	Landfilling, WtE, Composting, Recycling	398
Denmark	10,959	Composting, Landfilling, WtE, Recycling	325

Source: (Pujara et al., 2019)**;** AD: Anaerobic digestion; MBT: Mechanical biological treatment; WtE: waste to energy; -: not reported

Table 2: Types of earthworms and their applications

Type	Name	Applications
Epigeic	*Eisenia fetida, Eisenia Andrei, Eiseniella tetraedra, Dendrobaena veneta, Dendrobaena hortensis,* *Dendrobaena octaedra,* *Allolobophoridella eiseni*	• These earthworms either live near or on the soil surface or in the organic horizon. • They mainly feed on the decaying organic matter and show high rates of consumption, digestion and finally assimilation of the organic matter they feed on. • They play a crucial role as the transformers in the process of vermicomposting.
Endogeic	*Aporrectodea caliginosa,* *Aporrectodea rosea,* *Octolasion lacteum*	• These earthworms thrive in deeper soils and primarily feed on soil and its associated organic matter. • They are more resistant to the unfavourable environmental conditions like those of drought and scarcity of food.
Anecic	*Lumbricus terrestris*	• These earthworms thrive up to several meters in the soil profile. • They primarily feed on faeces, litter and decomposing matter and deposit their excreta on the surface.

Table 3: Reactions involved in various stages of anaerobic digestion

Sr. No.	Various Stages of Anaerobic Digestion	Reactions
1	Hydrolysis	$(C_6H_{10}O_5)n + nH_2O \rightarrow nC_6H_{12}O_6 + nH_2$
2	Acidogenesis	$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2\ CO_2$ $C_6H_{12}O_6 + 2\ H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O$ $C_6H_{12}O_6 \rightarrow 3CH_3COOH$
3	Acetogenesis	$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+HCO_3^- + 3H$ $C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2$ $CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 3H_2 + H^+$
4	Methanogenesis	$CH_3COOH \rightarrow CH_4 + CO_2$ $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ $2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH$

Table 4: Types of sensors, target application and domain of functionality in municipal solid waste management/monitoring

Sensors	**Target application**	**Domain of functionality**	**References**
Photovoltaic sensor, Optical sensor	Sorting of glass containers	Sorting system for recyclable glass containers	(Nivetha et al., 2019)
Load cell sensor	Monitoring of bin status	Automatically capturing the weight and identity of trash bins, as well as assisting in the identification of stolen bins	(Mamun et al., 2016)
Capacitive sensor	For energy recovery	For moisture content of MSW	(Vrancken et al., 2017)
Calorific value sensor	Incineration optimization	MSW combustion process optimization	
Hydraulic pressure sensor	Collection plans	Enhancement of collection plans by bin tracking	(Huang et al., 2019)
Tin oxide sensor	Measurement of landfill odor	Landfill gas odor measurement	(Ghosh et al., 2014)
Optical sensor	Measurement of container filling	To measure fill status of recycling point trash cans	(Yan et al., 2018)
Proximity and weight sensors	Monitoring bin status	Allows collection of waste more efficiently	(Sakurama et al., 2018)

Linear displacement transducer	Speedy and efficient waste collection	MSW collection with high efficiency, accuracy, and flexibility	(Rajput et al., 2009)
Volumetric sensor	Optimization of collection	Framework for improving solid waste collection	(Wu et al., 2019)
Resistive sensor	Measurement of moisture content	To measure moisture content of MSW *in situ*	(Tripathi et al., 2018)
Mid-infrared sensor	Sorting system for ceramic and glass waste	Detection of toxins present in waste glass recycling streams	(Bogomolov et al., 2015)
Capacitive sensor	Analyzing the status of the container's filling	Measurement of the wastebasket's fill level	(Kubra Isgor et al., 2015)
Infrared light-emitting diode	Routing and scheduling in real-time	Provides status of container filling every hour to aid in the implementation of dynamic scheduling and routing	(McLeod et al., 2013)

Highlights:

- Waste monitoring using high-end technologies has been discussed.

- Integration of technological approaches is needed for efficient waste management.
- Compiled environmental and economical relevance of waste management technologies.
- Strategic innovations in municipal solid waste management have been focused.
- Tools for hazard monitoring have been included.