Emerging Developments in Solid Waste Management for Urban Areas in India: Present Scenario, Obstacles and Prospects

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Abstract: Given India's rapidly expanding population, densely populated cities, varied cultural backgrounds, shifting dietary preferences, and changing lifestyles, municipal solid waste management (MSWM) has been an ongoing issue in recent years. As a result, towns have been dealing with a wide range of additional problems pertaining to the disposal, handling, and collection of solid waste. Improper management of municipal solid waste may lead to detrimental impacts on the environment, hazards to public health, and other socio-economic issues. With the goal of assisting researchers and the relevant authorities in creating more efficient plans, this paper provides a comprehensive overview of the current state of municipal solid waste management in India. This paper also examines the present scenario, major obstacles and future prospects of solid waste management in urban areas of India.
Keywords: municipal solid waste management, recycling, waste to energy, composting, sustainable cities, urban, India

1. Introduction

The agricultural-based economy of India is rapidly giving way to one centred on industry and services. At the moment, 31.2% of people reside in cities. Over 377 million people live in urban areas across 7,935 towns and municipalities. India, a vast nation comprising 29 States and 7 Union Territories (UTs), exhibits a diverse urban landscape. According to the (Census, 2011), there are 415 cities with a population exceeding 100,000, including 53 cities with a population of one million or more. Notably, three megacities — Greater Mumbai, Delhi, and Kolkata — boast ten million populations. The majority of cities with populations exceeding ten million serve as state capitals, union territories, or key commercial and industrial hubs. India's climatic conditions vary across four distinct zones: tropical dry, tropical wet, subtropical humid, and mountainous regions. As these regions have four distinct seasons — winter, summer, rainy, and fall — their occupants also have distinctive patterns of waste production and consumption. Nevertheless, researchers must depend on the currently available limited information due to investigations carried out by various institutions such as the Central Pollution Control Board (CPCB) located in New Delhi, the National Environmental Engineering Research Institute (NEERI) situated in Nagpur, the Central Institute of Plastics Engineering and Technology (CIPET) based in Chennai, and the Federation of Indian Chambers of Commerce and Industry (FICCI, 2009) headquartered in New Delhi are key entities involved in addressing municipal solid waste management (MSWM) in India, an essential part of sustainable metropolitan development, comprises the separation, storage, collection, transportation, processing, and disposal of solid waste in order to lessen the harmful impacts of solid waste on the environment. A wide range of diseases are spread by inadequately managed MSW(Kumar S. et al., 2009).

Advances in economics and technology have made stakeholders more interested in solid waste management (SWM), which is one of the most frequently investigated subjects in industrialized nations (Dijkgraaf & Gradus, 2004), (Shekdar, 2009). Considering to the high rates of population growth, the fast-increasing waste generation and categorizing patterns, along with the increasing urbanization and industrialization in emerging countries, MSWM is crucial (Troschintez & Mihelcic, 2009). Further, extra space is required for managing garbage (Idris et al., 2004).India generates nearly 12 million tons of inert garbage annually from street sweeping and building and deconstruction garbage, which makes up around one-third of all MSW in landfills.

The management of Municipal Solid Waste (MSWM) in India is regulated by the Municipal Solid Waste (Management and Handling) Rules of 2000 (MSWR). Urban local bodies (ULBs) throughout the nation are significantly concerned with the effective implementation of these rules. Single-use plastics have been a global concern recently due to their claimed hazards and lack of biodegradable properties Urban floods can originate due to the overproduction of plastic waste in metropolitan areas, which may clog drainage systems during the monsoon. Rivers and oceans become polluted when the microplastic combines with water (Anderson et al., 2016). Up to this point, the investigation has proven that microplastic damages aquatic life, specifically the food chain, and eventually plays an essential part in global warming. It has thus been identified as the primary factor that has caused the extinction of numerous of Earth's native species (Kumar & Agrawal, 2020). Only 9% of the 300 million tonnes of plastic waste generated annually worldwide are recycled, 14% are collected for recycling, and the remainder of the rubbish ends up in the ocean.

(Plastic recycling: an underperforming sector ripe for a remake, 2024). This information is based on a UNPD report. Figure 1 illustrates the global build-up of plastic garbage in grammes per km^2, mainly in the oceans.

The creation of toxic chemical waste by urban areas, including hospitals and manufacturers, is yet another problem related to MSWM. This waste contributes to respiratory problems and early mortality (Joshi & Ahmed, 2016). Although recycling has not kept up with expectations, India has become a major player in the industry in recent years (Bhattacharya et al., 2018). In landfills, inadequate handling of MSWs draws animals, rodents, mosquitoes, birds of prey, and scavengers, providing potential hazards to front-line staff and waste pickers. Still, a few Indian cities — Pune, Surat, Alleppy, Bobbili, and Panji — have shown a willingness to work around the SWM techniques utilized in this study. Furthermore, it has been found that the governments pay little consideration to advance treatment in favor of concentrating primarily on the collection phase. However, additional upgrading is also essential to resolve the MSWM problem. Modern material recovery has proven to be challenging, but the information industry can be included in the main streamlining of the MSWM procedure. However, in order for this vision ultimately to pass, government organizations need to contribute money and other resources, promote public awareness and promote engagement, and remove social taboos. Having every detail provided previously in one location might serve as a step toward sustainable, clean cities. As a result, the current study is a thorough assessment that considers all feasible MSWM strategies from the past to the present while also addressing the opportunities and problems for India's future urban cities.

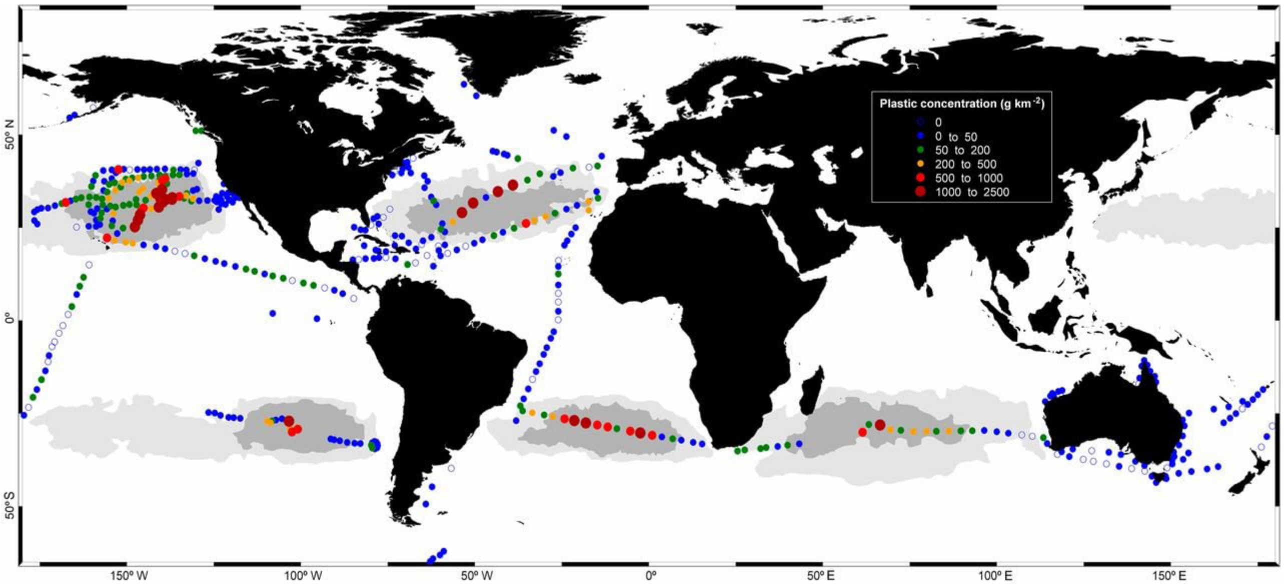


Figure 1. Concentrations of plastic debris in surface waters of the global ocean

2. Literature Review

2.1 Challenges and Efforts in Indian MSWM

2.1.1 Municipal solid waste quantity and generation rate

According to Sunil Kumar, over 143,449 MT of MSW are produced daily in India; of that amount, about 111,000 MT are collected, and about 35,602 MT are treated. The waste generation per capita/day from 2001 to 2018 varied significantly at an exponential rate that was strictly between 0.24 and 0.85, according to the CPCB's 2018 annual report on garbage generation by city. From this point forward, it is expected to grow rapidly (CPCB, Waste Generation and Composition, 2018a),(Sunil Kumar et al., 2017),(Annepu, 2012). The combined MSWM system status for all 29 Indian states is shown in Table 1.

Table 1. Status of Municipal Solid Waste Management (MSWM)

Parameter	Status
Population density	382 persons per square kilometre
Door-to-door collection	Implemented in 18 out of 29 States
Segregation of waste at the source	Practiced in 5 out of 29 States
Unsanitary landfill sites (number)	1285
Compost and vermicompost facilities operated by ULBs	95
ULBs under construction compost/vermi-compost facilities	173
Operating pipe composting facilities (number)	7000
Operating RDFs Facilities (number)	12
Operating Biogas Plants (number)	11 (6 operational), 645 total
Energy generation Plants (number)	11 (6 operational)
Solid Waste generation	143,449 metric tons per day
Solid Waste collection	111,000 metric tons per day (77.6% of total)
Solid Waste processing/treatment	35,602 metric tons per day (24.8% of total)

Note: ULBs = Urban Local Bodies. Source: Data from CPCB 2016, (Sharma & Jain, 2018), Census 2011 India.

Different factors, particularly temperature, the social and economic status of the population, and geographic location, impact the different kinds of garbage that are found in cities. Garbage generation in populated cities is currently on the rise. Waste variation shows strongly that different cities are unable to use the same technique which creates additional challenges for the municipalities. Despite a decline in the number of cases that are moving forward, municipalities appear to be falling behind and are unable to handle the problem.Larger capital cities such as Bangalore, Delhi, Mumbai, Chennai, Hyderabad, and Kolkata are responsible for a significant portion of India's solid waste generation (Figure 2). These areas have extremely dense populations, which results in a daily generation of heterogeneous solid waste that makes up roughly 70%–80% of all trash generated in India (MNRE, 2018).

According to the (MNRE, 2018) study, the nation produces a huge amount of trash due to its overpopulation in states like West Bengal, Gujarat, Maharashtra, Tamil Nadu, Uttar Pradesh, the National Capital Region, and Karnataka.

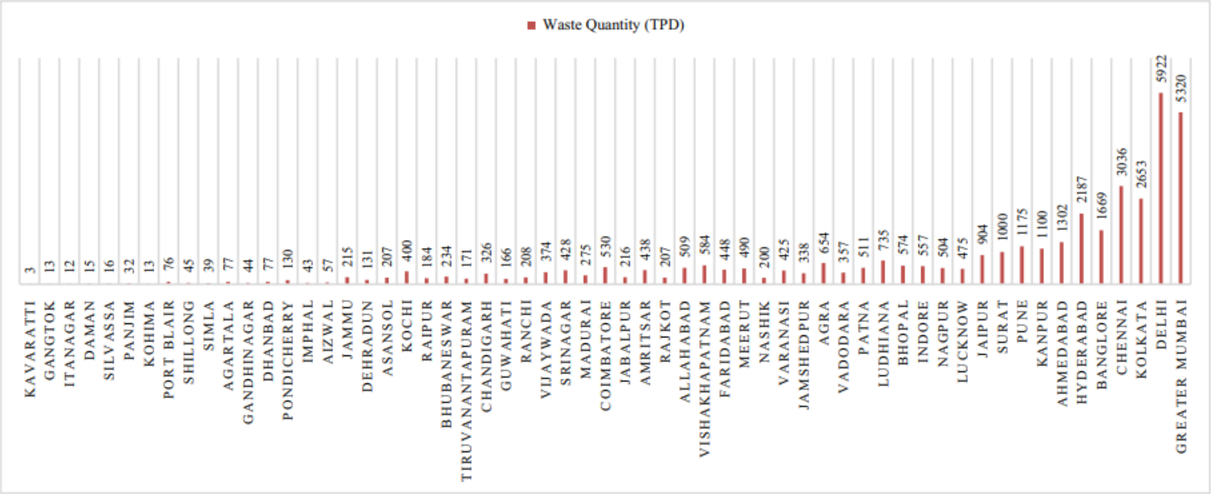


Figure 2. Waste Generation in Indian Cities: Tonnes per Day

2.1.2 Global Solid Waste Generation Trends Comparison

Projections indicate that global waste generation will surge to 27 billion tonnes annually by 2050. Presently, Asia accounts for one-third of the world's waste output, with substantial contributions from China and India. Waste generation in these countries varies between 0 and 449 kilograms per day per resident. Per capita daily weight of 0.50–0.9 kg(Modak, 2010). Waste generation on the Indian continent is predicted to vary from (334–661) MT/day to (468–714) MT/day in the East Asia-Pacific area in the year (2016–2050) assuming the existing conditions persist. Figure 6 illustrates that the average quantity of waste generated per person, based on available statistics, ranges from 150 g to 300 g. Globally, 7–10 billion tonnes of municipal garbage, including construction and demolition debris and industrial waste, are created each year.

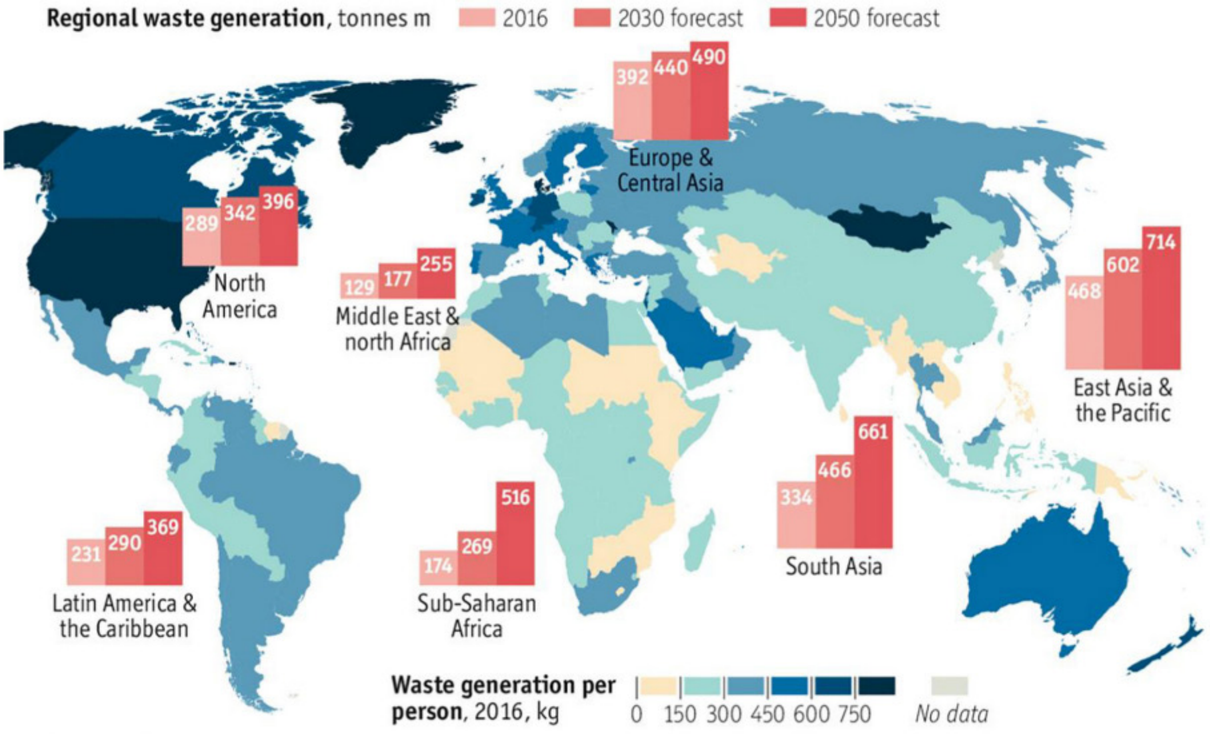
2.2 Elements of Municipal Solid Waste Management in India

2.2.1 Attributes and Constituents of Solid Waste

The makeup of waste has a substantial effect on waste management systems. Typically, higher-income demographics tend to utilize a greater quantity of packaged goods compared to lower-income groups. This inclination results in a higher presence of materials like paper, glass, metals, plastics, textiles, and glass within the waste streamdisparate populations (Sridevi et al., 2012). Additionally, MSW may include hazardous materials like paint, batteries, pesticides, outdated pharmaceuticals, and e-waste. Comparing the waste composition of typical Indian towns to wealthy nations, with reference to Figs. 8 and 9.

The only thing sustaining the economy of the unorganized sector is the make-up of the waste produced. According to earlier studies, organic waste makes up between 40% and 50% of solid waste composition, inert waste and construction/demolition waste make up 30%, and recyclable garbage makes up the remaining waste.Indian solid waste has an average calorific content that ranges between (15002200) Kcal/kg, lower when compared to industrialised nations because there is less waste from paper and plastic. Compared to developing nations, the solid waste has higher moisture content.

In addition, the World Bank has offered a forecast for the future and an assessment of the current state of affairs with regard to specific international regions. This illustrates the average waste generation per capita per day in 2016 according to “Waste Generation World Bank Org.” (bank, 2015). It falls into three categories: lower-middle income groups (0.16–0.79 kg), upper-middle income groups (0.1–1.2) kg, and lower-income regions (0.09–0.60 kg). Based on forecasts from 2016 to 2050, it is anticipated that by that year, regional waste output will have quadrupled globally (Figure 3).



Source: World Bank

Figure 3. Projected Global Waste Generation Trends (Ed.), 2018

Table 3 provides a comparative analysis of the solid waste generation across various regions in India, considering factors such as composition, moisture content, and calorific value. This analysis provides valuable insights into the diverse traits of waste produced across urban areas, states, union territories, and regional zones throughout the nation.

Table 2. Regional Overview of Solid Waste Composition

Region/city	MSW (MT/day)	Compostable (%)	Recyclable (%)	Inert (%)	Moisture (%)	Calorific values (Kcal/Kg)
Metro cities	51,402	50.89	16.28	32.82	46	1523
Other cities	2723	51.91	19.23	28.86	49	2084
Northern India	6835	52.38	16.78	30.85	49	1623
Eastern India	380	50.41	21.44	28.15	46	2341
Southern India	2343	53.41	17.02	29.57	51	1827
Western India	380	50.41	21.44	28.15	46	2341
Overall urban India	130,000	51.3	17.48	31.21	47	1751

2.2.2 Quality of Indian solid waste

In this case, with a carbon to nitrogen (C/N) ratio of (26 ± 5) % and a biodegradable fraction predominantly exceeding 50% (refer to Figs. 10 and 11), it suggests that organic waste can effectively contribute to compost and biogas production. Consequently, many Indian cities may opt for organic waste-based treatment methods. Conversely, certain locations such as Imphal, Aizawl, Itanagar, Kohima, Nashik, Ludhiana, and Pune exhibit notable calorific values. Following the extraction of valuable recyclables, waste-to-energy plants could potentially utilize refuse-derived fuels (RDFs) or resort to incineration. As depicted in Figure 4, a higher solid waste calorific value (HCV) proves advantageous for both RDFs and the incineration process. For waste-to-energy plants, calorific values 1500 kcal/kg and higher are deemed appropriate.

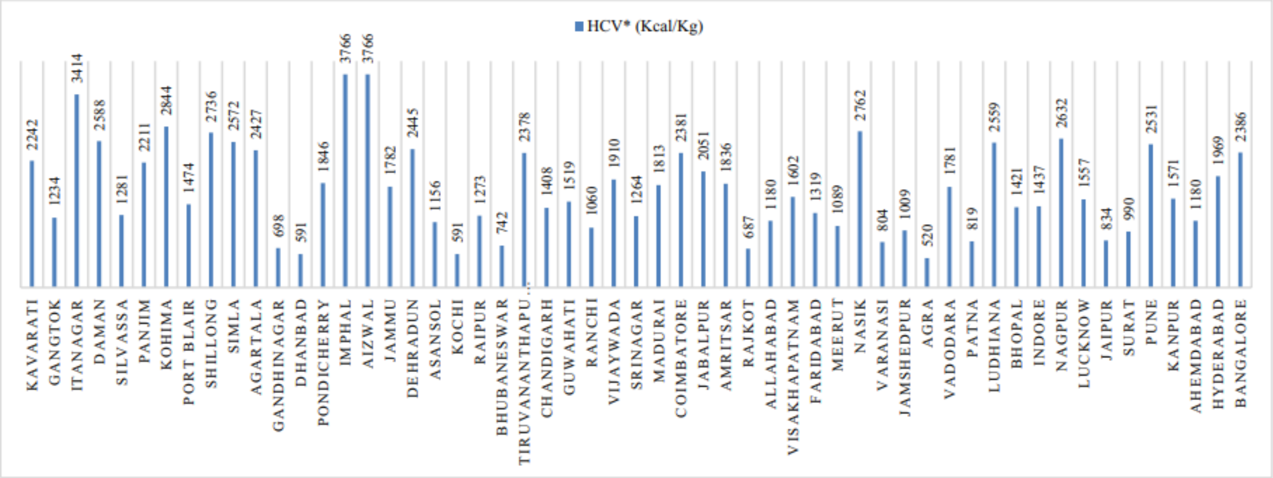


Figure 4. HCV Kcal/Kg(CPCB, Waste Generation and Composition, 2018a)

Appropriate processing of solid waste is essential for any waste management system to function effectively. According to (Annepu, 2012), the majority of municipalities do not have the requisite equipment and tools to manage this amount of unorganized trash. The prevalent waste management approach commonly adopted in India is depicted schematically in Figure 5. Manual labour predominantly undertakes the bulk of waste collection and handling, with the primary responsibility of municipal authorities being door-to-door garbage collection. At times, municipal bodies delegate waste collection, transportation, processing, and final disposal responsibilities to private entities. Nonetheless, the merchants' collected recyclable material was sold to nearby scrap dealers, consequently, these private entities often dispatch the collected waste to recycling facilities located outside urban areas. Therefore, rag pickers play a crucial role in the collection and processing of waste within privately organized cities.

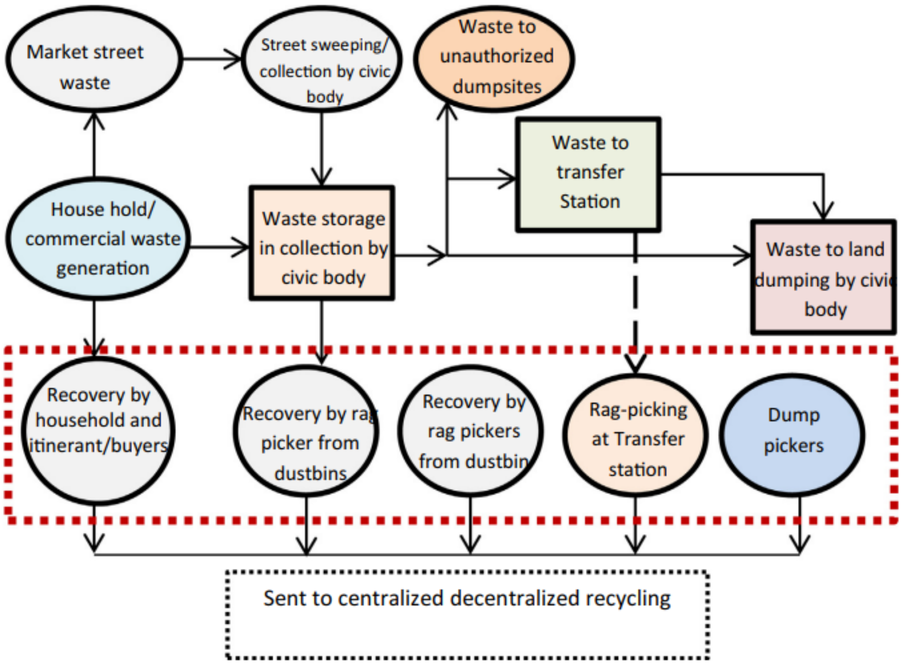


Figure 5. Diagram of Standard Municipal Solid Waste Management Process

3. Challenges in Municipal Solid Waste Management in India

3.1 Environment and health issues

Environmental degradation severely jeopardizes human health (Shukla et al., 2000). Failure to use proper gloves, uniforms, and safety equipment exposes both formal and informal workers to immediate health risks. Living near the disposal sites exposes a person at high risk of gastrointestinal parasites (Guisti, 2009). Methane is emitted from open dumps when biodegradable waste breaks down in anaerobic conditions. It is a major source of fires and explosions and contributes significantly to global warming (Slagstad & Brattebo, 2013).

Regarding receiving water and soil, odour and leachate migration are issues (Muhammad et al., 2020). Tyres that are disposed of in landfills gather water, which attracts mosquitoes and raises the risk of illnesses like dengue, malaria, and West Nile fever, among others. According to (Ghosh, 2016) and (Annepu, 2012),respiratory ailments are notably attributable to the fine particles and haze emitted from the unregulated burning of waste at dumpsites. Hazardous gases like carbon monoxide (CO), carbon dioxide (CO2), particulate matter (PM2), mercury, and polycyclic aromatic hydrocarbons (PAHs) exert a severe impact on both newborns and adults.Plastic pyrolysis also has an impact, and even water contaminated with arsenic can cause cancer and death (Ghosh, 2016), (Ashiq Ahamed et al., 2020).

According to (Ghosh, 2016) and (Ashiq Ahamed et al., 2020), arsenic can cause cancer and even death.Based on the assessment carried out by the expert committee of the Indian Ministry of Urban Development, the primary capital and maintenance costs for class 1A cities varied between Rs. 900 to Rs. 269 per capita annually (Mani & Singh, 2016). Municipalities and Urban Local Bodies (ULBs) encounter challenges when the waste sector lacks efficient financial and managerial mechanisms alongside comprehensive policies. Since it is not profitable, unsegregated garbage has neither been practiced nor put aside. In order to promote SWMS across the country, the Indian government has allocated grants and funds through the 12th and 13th finance commissions. These financial resources are designated for initiatives such as the Jawaharlal Nehru National Urban Renewal Mission (JNNURM) and the Urban Infrastructure Development Scheme for Small and Medium Towns (UIDSSMT). Specifically, a total of Rs. 20,000 crores have been earmarked under the Swachh Bharat Mission (Mani & Singh, 2016).

3.2 Issues Arising from Inadequate Government Policy Implementation

In crafting national policies, a paramount consideration revolves around effectively managing the solid waste generated within the country(Azahar & Wee, 2014). This issue is particularly pronounced in urban areas due to factors such as economic growth, rural-to-urban migration, erratic land utilization practices, and notably, the absence of robust legislation governing solid waste management. Efforts to establish a coherent institutional framework for addressing this challenge are underway. The Swachh Bharat Mission (SBM), led by the Ministry of Urban Development (MoUD) within the Indian government, takes the forefront in spearheading these initiatives. Local municipal bodies (ULBs) play a pivotal role in orchestrating nationwide efforts aimed at ensuring sanitation in cities, with a specific emphasis on integrating solid waste management systems with societal concerns(Mani et al., 2015).

3.3 Challenges in Operation of MSWM Processes

3.3.1 Segregation and collection

Due to the rarity of segregation, municipalities typically rely on a daily staffing shortage to manually collect unsorted waste from narrow and severely congested streets, door to door (CPHEEO, 2016). Data from State Pollution Control Boards and Committees, spanning the years 2009 to 2012, highlight that in the fiscal year 2011-2012, the nation generated an average of 127,486 tonnes of municipal solid waste (MSW) per day. Among this volume, 89,334 tonnes, equivalent to 70%, were successfully collected.

3.3.2 Storage and transportation

The majority of the solid waste that is generated is stored in both private and public receptacles. The inhabitants usually harness one container for mixed waste, especially during the rainy season, which frequently turns out to be inadequately handled and full of leachate.

Weekly visits are carried out by the trucks which collect solid waste; in most locations, these trucks are unenclosed, have a little capacity, and gather waste manually. The scarcity of land for trash disposal poses an even more challenging issue(Kumar & Agrawal, 2020).

3.3.3 Treatment and final disposal

Due to a lack of finance and technological expertise, India is having difficulty disposing of its municipal solid waste (Kaushal et al., 2012). The two most advanced waste disposal methods used in India are composting (aerobic composting and vermi-composting) and waste-to-energy (WTE), which includes incinerator, palletization, and bio-methanation. WTE programs for the disposal of MSW are a relatively new concept in India.

These have not gained momentum in India despite being tried and tested in industrialized nations with good results; this is mostly because their financial viability and sustainability are still being evaluated (Sharholy et al., 2008). The 500 TPD MSW capacity and 6 MW electricity generation capacity of the Vijayawada waste-to-energy endeavour, developed by Shriram Energy Systems, Ltd., Hyderabad, have been in use since December 2003. Located near Hyderabad in Gandhamguda, another facility operated by M/s SELCO International Ltd. has been operational since November 2003. This facility has the capability to process approximately 700 tonnes per day (TPD) of municipal solid waste and generate 6.6 MW of electricity. Additionally, M/s Shriram Energy Systems Ltd., based in Hyderabad, is set to launch a third waste-to-energy project in Vishakhapatnam. Furthermore, a 600 TPD waste-to-energy project is under construction in Chennai (Kumar S. et al., 2009). However, it's noteworthy that only a small fraction, around 6–7%, of municipal solid waste (MSW) in India is converted to compost (Annepu, 2012). The remaining MSW is disposed of by landfilling. Although it has been adopted in India, a waste-to-energy system for the disposal of solid waste that combines incineration and bio-methanation makes a minimal contribution to the current situation (Figure 6).

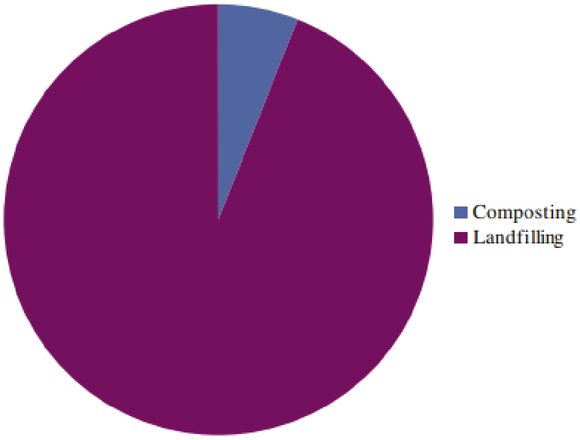


Figure 6. Status of solid waste disposal in India

4. Future Prospects and Opportunities for Indian Cities

4.1 Illustrative Examples of Effective MSW Practices in India

Different Indian cities have taken varied approaches to dealing with solid waste; some have accomplished varying degrees of segregation, recycling, reduction, and reuse, while others are content to just try to sweep their trash under the carpet. A few best cases that illustrated possible strategic prospects and a vision for India's future were discussed.

4.1.1 Surat city, Gujarat: A quick overcome

The nation was alerted to the plague epidemic in Surat City (Annepu, 2012). A pandemic of fatal diseases struck Surat town in 1994 (Bharti et al., 2017). Because of the flood-like circumstances created by excessive rains along the city's coast, rats and other rodents have easy access to the urban area. The situation worsened to the point where there were large-scale deaths and citizen migration, while countries such as the United Kingdom refrained from fighting.Under the leadership of a recently installed team of municipal commissioners, a concerted effort was undertaken to transform the city within a tight timeframe of eighteen months. Implementing a novel approach, the diligent sanitation crew of Surat embarked on a strategy that involved eliminating traditional dustbins from neighbourhoods and instead opted for door-to-door waste collection to maintain cleanliness. This initiative has catapulted Surat into the ranks of the nation's cleanest cities, serving as a beacon of inspiration for others.

4.1.2 Alleppey, Kerala: Pioneering Decentralized Waste Management

Alleppey, also known as Alappuzha, a thriving municipality in Kerala, has pioneered an innovative decentralized waste management system. With a population of approximately 0.19 million and covering an area of 46 square kilometres, Alappuzha is home to 40,000 households distributed across 52 wards. To address waste management challenges, the municipality has introduced pipe composting for residences with lower waste volumes, while those with ample land receive portable biogas plants from IRTC at a subsidized cost of Rs. 17,500. These biogas plants, priced at Rs. 13,500, can process 5 to 7.5 kg of organic waste daily, producing 2 to 3 hours of biogas. Notably, facilities generating biogas qualify for a substantial 75% subsidy through the "Suchita Mission." Additionally, residents with limited space and financial resources are encouraged to utilize cluster biogas plants owned by their neighbours for waste disposal. Remarkably, Alappuzha municipality saved Rs. 7 lakhs in the fiscal year 2013–14 by eliminating the need for diesel trucks for waste transportation. The effectiveness of Alleppey's decentralized waste management model stands as a compelling exemplar for other urban local bodies to follow (Balasubramanian, 2018).

4.1.3 Bobbili, Andhra Pradesh: Leading the Way in Composting Practices

Bobbili, recognized as one of the cleanest cities worldwide, has a population of around 0.057 million, residing across a land area spanning 25.6 square kilometres. Despite its cleanliness accolades, the city grappled with the challenge of efficiently managing its daily garbage output, amounting to 14 metric tonnes. As of 2008, waste management posed a significant concern for Bobbili.Trash mounds, public littering, and frequently clogged sewers — especially with polyethene bags — were among the main problems. It has suffered from the excessive fuel consumption of the collection vehicle and the improper handling of waste. Residents of the area were asked to separate their waste at the place of origin into two categories: dry waste and moist waste. Bobbili separates about 70% of its organic waste into two containers.

Four sizable bins are used to carry around 88% of the waste that management personnel have sorted and classified, including horticulture, kitchen, plastic, and inert waste, to the SWM Park. The collection of 14 MT of waste has been allocated to a 3.4 ha parcel of land; the 1.4 MT of recyclable inorganic waste that is gathered is delivered to the local scrap market. Approximately 150 kg of cow manure and 3.1 metric tonnes of organic waste were fed into the biogas plant, in addition to the 350 kg of mix and leachate utilized for vermi-composting. Bobbili handled solid waste and collected Rs. 7.26 lakh in fees annually to pay for trash managementThe total expenditure for waste management amounts to Rs. 77.66 lakhs. Bobbili is keen on marketing all its organic waste and compost locally as a municipality, potentially yielding daily revenues ranging from Rs. 60,500 to Rs. 2,58,500. Additionally, the town deserves acknowledgment for accomplishing 100% waste collection and segregation (Balasubramanian, 2018).

4.1.4 Panaji, Goa: Linking User Charges to Waste Management

The state capital of Goa, Panji, is home to 1.45 million people and occupies 36 square kilometres. This city was well-known in the early 1990s for its unclean civic conditions, inadequate infrastructure, and weak MSWM. In 2000, Panaji took a significant step forward by establishing the NGO People's Movement for Civic Action and the Garbage Management Committee. Over the course of the year, the Corporation of the City of Panaji (CCP) meticulously examined its house-to-house waste collection initiative, engaging with approximately 200 homeowners. The success of the door-to-door collection system paved the way for a comprehensive municipal revitalization program, launched in early 2003, aimed at achieving a “bin-free city” status.In order to enhance waste management efficiency, the Corporation of the City of Panaji (CCP) has divided the city’s 115 residential colonies into 12 distinct waste management zones. Each zone is supervised by an appointed supervisor tasked with overseeing waste transportation and collection activities within their designated area. As per a comprehensive study conducted by the Centre for Science and Environment (CSE) in 2015, dry waste constitutes approximately 64% of Panaji’s waste, while wet waste accounts for the remaining 36%. Residents are mandated to pay an annual sanitary fee of Rs. 365 to the CCP for solid waste management (SWM) services. This fee structure is intricately linked to property taxes, with business hotels being levied charges ranging from Rs. 300 to Rs. 10,000 based on their waste generation. Moreover, the CCP operates a recycling station where PET bottles are separated from other plastic waste streams. This facility utilizes organic waste converters (OWCs) for processing wet waste and features recycling stations dedicated to dry waste segregation.To bolster waste management infrastructure, the CCP has established seventy composting units across the city, including six OWCs capable of handling six tonnes of waste daily(Agarwal et al., 2015).

4.1.5 Pune City, Maharashtra: Spearheading Biogas Plant Initiatives

Pune is steadfast in its commitment to utilizing biogas as a means to enhance urban cleanliness while striving to minimize waste sent to landfills. With a population of 3.5 million residing across a 244 square kilometre area, the city generates an average of approximately 400 grams of solid waste per person. Projections indicate that by 2031, Pune is anticipated to produce around 3600 tonnes of trash annually. In response to this mounting challenge, the city is actively exploring advanced technologies, including biogas plants, to effectively manage its waste. Employing decentralized methods such as thermal gasification, Pune is implementing a multifaceted approach encompassing vermicomposting, Refuse Derived Fuel (RDFS), recycling, and waste-to-energy systems.According to recent reports, Pune processes over 2100 t of rubbish every day, with 70% of the waste coming from organic sources in households.With a population of approximately 4,000, the first municipal biogas plant was built using the colony concept. It produced 150 t of compost in addition to 375 units of energy, which was sufficient to run 250 streetlights. In 2014, there were about 20 of these biogas plants operating; by 2015, there may be 27 or more(Thakare & Nandi, 2016).

The models that Pune Municipal Corporation, PMC, owns are built on public-private partnerships. The biogas plant operator receives maintenance payments of Rs. 6,00,000 per month, with annual increases of 10% to 15%. The facility was established in 2010 at a cost of Rs. 60 lakhs. As of right now, PMC is paying between Rs. 1300 and Rs. 1400 per tonnes to transport one container of waste to the facility due to an increase in price of Rs. 30 lakhs. Additionally, hotels began providing cooperatively managed separated waste, which households may then send straight to the bio-Methanation plant. Additionally enforced on the producers of unsorted garbage is a PMC penalty scheme. An extra property tax credit for buildings with environmentally friendly amenities like compost pits, solar heaters, and rainwater collection systems. During routine inspections, PMC makes sure there is no foul play. If anything is found to be malfunctioning, they also cancel the reimbursement (Wilson & Rodic, 2017).

5. Materials and Methods

5.1 Exploring Strategies and Options

5.1.1 Organic Waste (Wet Waste): Development of Composting Facilities

Composting is an option for the separated organic portion of municipal solid waste. The microbiological reaction that breaks down organic matter produces energy, organic fertiliser, and certain byproducts like CO2, CH4, SO2, and H2S. Two widely recognised methods of composting are the aerobic methods (pit/pot composting, vermicomposting, windrow composting, and aerator drum composting). The latter method yields compost that is free of pollutants. The production of vermicompost using earthworms under carefully controlled conditions (Alok et al., 2017) is supported by the Indian government’s Ministry of Fertiliser and Chemicals.Rich in grade compost can be supplied to nearby farmers at a discounted price or used for gardening purposes using a scientific technique. Facilities for vermicomposting have already been introduced to the residential and industrial markets in the USA, Canada, Italy, and Japan. The time has come for India to consider the commercial application of vermicompost technology.

5.1.2 Waste-to-Energy Plant: Conversion of Dry Waste

By using microbial interaction and anaerobic digestion, methane gas can be extracted from organic waste without the need for air. As an agro-based economy, India has proven it can convert agricultural waste into enriched manure and biogas (Prakash & Singh, 2013), (Paritosh et al., 2017). The biomethane generated by the two-stage process can be converted into electricity using the generator. Based on a study conducted for Agartala, it is projected that the municipal solid waste

(MSW) generated amounts to 249.41 metric tonnes. The anticipated yield of biogas is expected to increase substantially from 52,376.10 cubic meters per day in 2021 to 108,559.5 cubic meters per day by 2051 (Sukanta et al., 2019). In Lucknow, a waste-to-energy facility was established in 2003 by Asia Bio-energy Ltd., Chennai, following the BOOM (Build, Own, Operate, and Maintenance) model. This facility has the capacity to generate 5 MW of electricity using 500–600 tonnes of MSW (Axelsson & Kvarnström, 2010). Furthermore, in accordance with the 2016 revision of Solid Waste Management (SWM) standards, policies on waste disposal prioritize the utilization of incinerators, refuse-derived fuel (RDF) facilities, bio-methanation plants, and other scientifically advanced treatment facilities while discouraging the outdoor burning of waste.

5.1.3 Advanced Landfill Sites: Management of Mixed Waste

Utilizing a landfill, which involves the systematic deposition of discarded waste in layers with soil covering, remains one of the most cost-effective methods of waste disposal, particularly beneficial in the context of developing nations. Following deposition, the mixed waste undergoes compaction and is then covered with soil and vegetation, as detailed by(Daskalopoulos et al., 1998). The top and bottom liners are essential to the construction of a landfill site because they let methane gas into the system. Leachate and leaks find their way to the groundwater through the soil (Gupta et al., 2015). Landfill sites release hazardous gases and generate solid garbage when complex compounds such as alcohols, hydrocarbons, heavy metals, methane, carbon dioxide, CO, N2, SO2, and H2S gases break down (Fadel et al., 1997). Based on estimates, 442 m3 of landfill gas with a heat value of 19,730 kJ/m3 and 55% CH4 are produced during the decomposition of 1T of MSW. To protect the environment from leachate and greenhouse gases, it is ideal to make a sizable capital expenditure. Additional requirements include land acreage, labour, technical equipment, and other scientific feasibility norms (Pan et al., 2017).

An investment of Rs. 46 crore is expected to yield 24 MW of power generated from landfill sites spanning 150 acres in Narela Bawana, Delhi, there is a facility designed to handle 2000 tonnes of solid waste. Through the process of gasification, municipal solid waste (MSW) is converted to produce synthetic natural gas (SNG) from syngas,suitable for various transportation applications, as noted by (Zehua Pan et al., 2019). Additionally, research by (Florence et al., 2019) suggests that slag derived from MSW could be utilized in nickel-based catalysts for the production of naphthalene steam. The management of battery waste involves a comprehensive approach encompassing reduction, recharging, and recycling through pyrometallurgical, mercury distillation, hydrometallurgical, and specialized metal recovery processes, as outlined by (Kuchhal & Sharma, 2019).

5.1.4 Inorganic Waste (Dry Waste): Incineration Techniques

As per (Zaman, 2010), waste incineration is a method that employs raw feedstock to generate energy in the form of both power and heat. This method involves burning the feedstock at temperatures around 850°C in the presence of oxygen, resulting in the production of various by-products. These by-products include solid residues such as "bottom ash," tar, steam, as well as gases like carbon dioxide, as highlighted by (Kumar & Agrawal, 2020). Several types of incinerators were identified by (moustakas & loizidou, 2010), including "fluidized-bed," "rotary-kiln," "fixed grate," and "moving grate." In Indian cities, incinerators have been found to be largely used by hospitals and biological treatment institutes. A great deal of research has been done on the byproducts of municipal solid waste incinerators, such as fly ash bricks and blocks that are used to build roads and structures (sabbas et al., 2003).

An incinerator facility that was built at Timarpur, Delhi, in 1987 and has a 300 Tonne daily capacity to burn waste produces 3.75 MW of power. Owing to the solid waste's low calorific values, it was discovered to be idle and the investment was squandered. For the process, it is essential to have high calorific values exceeding 1500 Kcal/Kg and a reduced moisture content (Annepu, 2012). Utilising fly ash from incineration demonstrates the material's potential as a byproduct and aids in the reduction of major air pollution (Phua et al., 2019). The essential limit point for fly ash addition to cement is between 5% and 10% (Yin et al., 2018).

5.1.5 Pyrolysis technology: Hazardous waste

It is feasible to process municipal solid trash, even if it would cost an enormous amount of money originally. Pyrolysis is a thermal decomposition technique that entails heating solid fuel materials without the presence of oxygen. This approach converts solid fuel sources into diverse byproducts, comprising liquid substances such as bio-oil or tar, solid residue referred to as char, and combinations of syngas. The production of bio-based oil involves two main processes:slow pyrolysis, which yields charcoal, and fast pyrolysis, as explained by (Kumar & Agrawal, 2020). However, one of the notable challenges associated with pyrolysis treatment is the complex array of byproducts that must be carefully managed to prevent environmental contamination. Due to the high temperatures involved and the presence of hazardous gases such as carbon monoxide (CO), additional treatment steps are often required. Plastic waste, owing to its significant potential as a fuel source with high calorific value, presents an opportunity for recovery through controlled pyrolysis processes, as suggested by (taherymoosavi et al., 2017). The procedure will protect the environment from plastic's harmful consequences in the future. the primary hydrocarbon breakdown caused by the Ca support. In addition to eliminating HCl, the calcium assistance aided in the breakdown of dienes and alkynes. Product gas had a composition akin to "reformate fuels" used in "solid oxide fuel cells" following the "catalytic treatment" with NiCa(veksha et al., 2018). PET waste and flexible plastic packaging may be converted into multiwalled carbon nanotubes for electrocatalysis and pyrolysis oil (veksha et al., 2020). The fabrication of supercapacitor electrodes for charge storage can be enabled through the two-stage process of pyrolysis and vapor deposition using mixed plastic waste.

5.1.6 Construction and Demolition Waste: Reuse and Recycling of Building Materials

The economic growth of metropolitan regions has culminated in a rise in the amount of C&D garbage generation in municipalities (Ram V & SN, 2017). Excavated materials are included in C&D (gayakwad & Sasane, 2015). Construction and demolition waste encompasses a wide array of materials, including concrete, brick, plaster, tiles, asphalt concrete, metal, steel, plastics, wood, asphalt, and concrete rubble. The implementation of the Solid Waste Management (SWM) rules in 2016, which align with the SWM and C&D requirements, imposes significant obligations on waste producers (MoEFCC, 2018b). However, innovative approaches can be employed to mitigate these challenges. These materials can be repurposed as raw materials in authorized upcycling facilities for various purposes, such as road construction, drainage pipes, and the production of affordable building materials like sand, bricks, gravel, and tiles. Plastic waste can undergo recycling processes and be reintroduced into the market, while high-quality lumber and salvaged metal can be sold to recycling industries for utilization in furniture manufacturing.

5.1.7 Innovative Approaches for Municipal Solid Waste Management

The methods of transportation and collecting depend on vacuuming (Ciudin et al., 2014). solid waste sorting using robots and sensors, The metal-organic framework-based enhanced NOx detection systems (Sarc et al., 2019). Agriculture and food waste, plastic-eating worms, biomass to ethanol & briquets production (pandiyan et al., 2019). Using plastic trash to make alternative fuel and paver tiles. In a study conducted by (Maharjan et al., 2019), coffee bean dust and Sal wood saw have been identified as promising electrode materials for vanadium redox flow batteries.

6. Discussion

Although the average amount of solid waste produced globally per person is far less than it is at the moment, the extraordinarily high population density is a major cause for concern. While packaging waste (paper, cardboard, plastic, etc.) from most industrialized countries is typically produced at low moisture contents, most organic material in the composition of solid waste in India is quite wet.Waste generation patterns across different Indian states and regions exhibit variations in terms of quantity, quality, and typology. The low calorific value and high moisture content are common for most states and cities. The budget and resources that are available, the tactics that are adopted, the planning techniques used, the amount of land that is available, and the size of the necessary recycling and processing facilities all range significantly. Trash separation at the site of origin is one of the primary problems Indian towns faces. It must be done to address the societal judgments connected with waste and the group of mostly marginalized individuals who are involved in it. In order for the waste management system to progress, public awareness is required. The context-specific consideration and evaluation of SWM's effects on human health and the environment is crucial. Numerous monies have previously been spent without a careful study or all-encompassing development plan. A small number of towns were able to establish a successful door-to-door collection system because of the poor execution of government laws.

Although collection vehicles are unable to perform daily collections, solid waste storage creates further difficulties. Additional bins often face issues of overflowing at their joints, leading to the accumulation of leachate.These bins are often targeted by ragpickers and also attract other animals like cows, street dogs, and rodents. The solid waste transportation system is still in its nascent stage of development, primarily due to insufficient infrastructure. In densely populated urban areas, decentralized waste treatment is rarely implemented due to land constraints.Moreover, numerous waste-to-energy and recycling facilities either ceased operations or are functioning at diminished capacity owing to a scarcity of high-value solid waste, thereby exacerbating the situation. Other variables that contribute include unplanned financial commitments and inadequate infrastructure for the treatment and recycling of solid waste. The unstructured informal waste and the formalised trash system need to work together.Moreover, since municipal solid waste (MSW) is typically managed by untrained individuals lacking safety equipment, it necessitates prompt removal.

Creating a workable treatment and recycling plan for Indian MSW is made more difficult by the shifting waste typology, but it also offers opportunities. Considering that organic (wet) waste constitutes a substantial portion of India's solid waste composition, there is a pressing need for the country to prioritize the implementation of decentralized waste management systems. This is due to India's vast potential for creating biogas and compost using a range of tried-and-true techniques. Both centralised and decentralized incineration technologies could be developed using the residual dry and inorganic fraction to produce refuse-derived fuel (RDF). Technologies like solid waste gasification and pyrolysis require specialized land and equipment for scientific monitoring, in addition to a substantial initial capital expenditure. The Government of India has implemented amendments and established specific guidelines for managing various types of waste, including building and demolition waste, e-waste, and other hazardous materials, through regular assessment and monitoring protocols. In certain regions, the implementation of user fees, penalty systems, and reward mechanisms can play a crucial role in fostering an efficient solid waste management (SWM) system. Moreover, the integration of advanced technologies such as the Internet of Things (IoT), Information, Education, and Communication (IEC)-based systems, and GIS/remote sensing can expedite public awareness efforts. This, coupled with the active participation of private entities, non-governmental organizations (NGOs), self-help groups, and the collaboration of all relevant departments, can significantly contribute to the success of municipal solid waste management(MSWM), address the demand for energy and materials, and pave the way for the creation of valuable assets for India in the future.

7. Conclusion

Despite its potential, waste continues to be perceived as a significant problem in many parts of India, particularly in areas with high population density where waste segregation at the source remains a challenge.This challenge is further aggravated by inadequate assessment of waste volume and infrastructure standards. As a developing nation, India faces a multitude of hurdles in municipal solid waste management (MSWM), compounded by social taboos and public perceptions surrounding waste management practices. However, several case studies of municipal cities showcase positive strides towards establishing effective solid waste management systems through the adoption of decentralized composting and biogas production facilities. Innovative solutions are imperative, given India's unique garbage compositioncompared to developed countries.Effective processing and recycling measures are crucial to enhancing wasteincorporation. This entails segregating solid waste at the source, with dry waste allocated for energy plants, Refuse Derived Fuel (RDF) facilities, recycling, and reuse, while wet waste is earmarked for composting or biogas production. Consequently, the aim is to minimize the volume of waste ending up in landfills or designated areas. Moreover, the exploration of advanced treatment techniques like gasification and pyrolysis is warranted, considering their environmental impact and cost-effectiveness before widespread implementation. It is possible to manage solid waste at multiple sources using both centralised and decentralised approaches in order to truly achieve sustainability in the MSWM system. The modest but well-organized informal waste sector, in addition to public and commercial organizations, is crucial in solving MSWM challenges and turning them into opportunities for India's future cities.

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