Status of integrated solid waste management and its practices in the twenty-first century in India

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Integrated solid waste management is an important challenge as well as an opportunity for public authorities, academicians, researchers and policymakers. The lack of understanding about the issues related to municipal solid waste management (MSWM) among different stakeholders and the associated cost makes the process challenging. This study was conducted based on the literature, reports and data available in public domain. India has the second largest population in the world, and its urbanization has posed many challenges for MSWM. The objectives of this study were to quantify the MSW generation, treatment and disposal rates in different states of India in recent years of the 21st century. We explain the geographical distribution of per capita generation of MSW in different states and Union Territories of India, considering the data from the Central Pollution Control Board, New Delhi. We observed that Odisha and Delhi had the highest per capita generation of waste in the country. Karnataka reported the highest percentage rise in per capita generation of MSW from 2014–15 to 2019–20. An in-depth study of the treatment methods and status in different states has also been reviewed by us. Maharashtra reported highest treatment of MSW in 2019–20 and also had the maximum number of landfills in India.

Keywords: Disposal, energy recovery, integrated solid waste management, landfills, per capita waste generation, recycling.

DURING the 20th century, solid waste management (SWM) practices in the developing nations were of a primitive type, which was also the case in developed countries[1]. Waste or garbage, if generated and collected, usually ends up at a local dump or is burnt openly to minimize the volume of solid waste, with public health risks due to the generated waste or garbage[2]. Over time, with technological advancements in different fields of products and services, solid waste management practices have also become robust[3].

Waste can be categorized as hazardous and non-hazardous. Non-hazardous waste is that which does not pose a threat to human health and the environment[4]. It includes construction and demolition debris, non-hazardous waste from industry and hospitals, mining waste, oil and gas waste, agricultural waste, municipal sludge, auto bodies, trees, wastes from residential areas[5,6]. Hazardous waste such as pesticides, batteries, electronic wastes, etc. are inappropriately managed wastes from residential areas those pose serious threat to human health and environment; thereby necessitating strong and robust storage and disposal mechanism and legal framework. On average, globally, out of the total waste generated, 95% is non-hazardous and 5% is hazardous; and municipal solid waste (MSW) comprise 2% of the total non-hazardous waste[7,8]. Although MSW contributes a small fraction to the total waste production, it is the primary cause of all the industrial waste generated in processing and providing products and services to society[9]. Therefore a standard procedure and regulation needed for proper management to reduce waste generation at the regional level[10].

MSW includes solid waste from residential, commercial, institutional and industrial sources[11]. This includes garbage or food waste, and rubbish like old tin cans, newspapers, tires and packaging materials[12]. Rubbish also includes thrash, which is combustible and non-combustible[13]. Solid waste generation can be modelled as the sum of material recovery and discards[14]. Material recovery refers to the extraction of materials from the waste stream to recycle and compost[15]. Discards refer to the remaining materials after recovery that are to be buried and burnt[16]. The municipal solid waste management (MSWM) deals with controlling the generation, collection, transfer, processing and disposal of solid waste[17]. It is primarily associated with the management of compositional and physico-chemical characteristics such as weight, volume and size of the solid waste[18].

India is the second most populated country in the world and ranks third in solid waste generation[19]. Many metropolitan cities are mushrooming in the country in recent years[20–22]. The average per capita solid waste generation in India is 0.14 kg/day. Environmental impact assessment of MSW in developing countries like India has been one of the most important disciplines for research in recent decades. Most of the earlier works on MSW in India were on major cities[23–25].

In this study, a review of the trend and status of MSW generation, treatment, and disposal practices during the beginning of the 21st century in India has been carried out. We have explained the geographical distribution of per capita generation of MSW in different states and Union Territories of India. The findings provide an outlook on the spatial and temporal variation across the country in solid waste generation. The magnitude of treatment of MSW has also been evaluated among different states of India. In this study, different available management practices and their sustainability in India have also been explored. Finally, the best practices of SWM have been suggested for the country.

The MSW generation is an integral function of the literacy, lifestyle, commercial activities, food habits, cultural set-ups, migration, geography and climate of a region[26]. In this study, we have estimated the per capita MSW generation during 1999–2000 for 22 different cities in India (Figure 1). The estimations were done based on MSW generation and population data available for the major cities of India.

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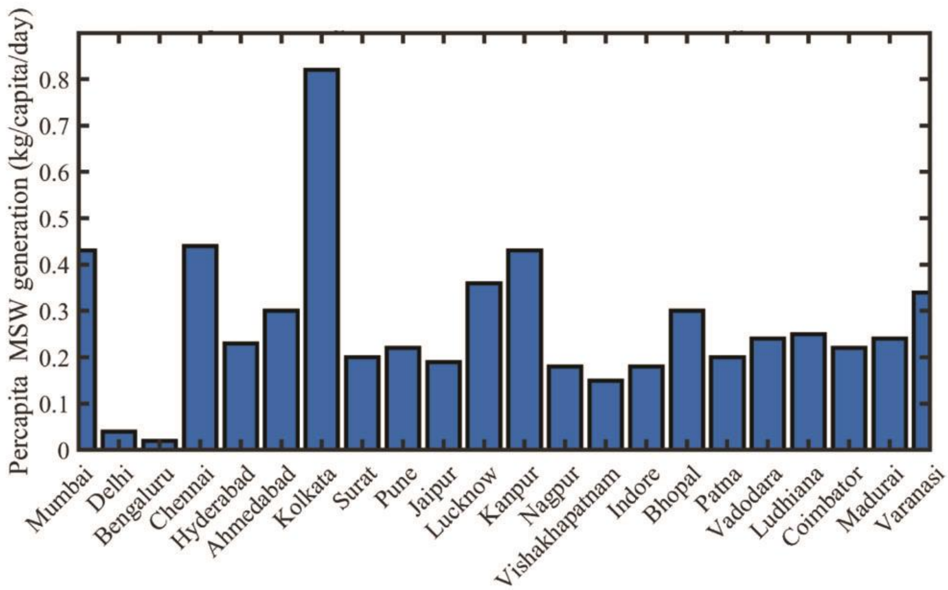

Figure 1. Per capita municipal solid waste (MSW) generation in 22 cities across India during 1999–2000. The per capita MSW generation was calculated using the population of major cities only. Source: Central Pollution Control Board (CPCB) Annual Report on MSW, 2000.

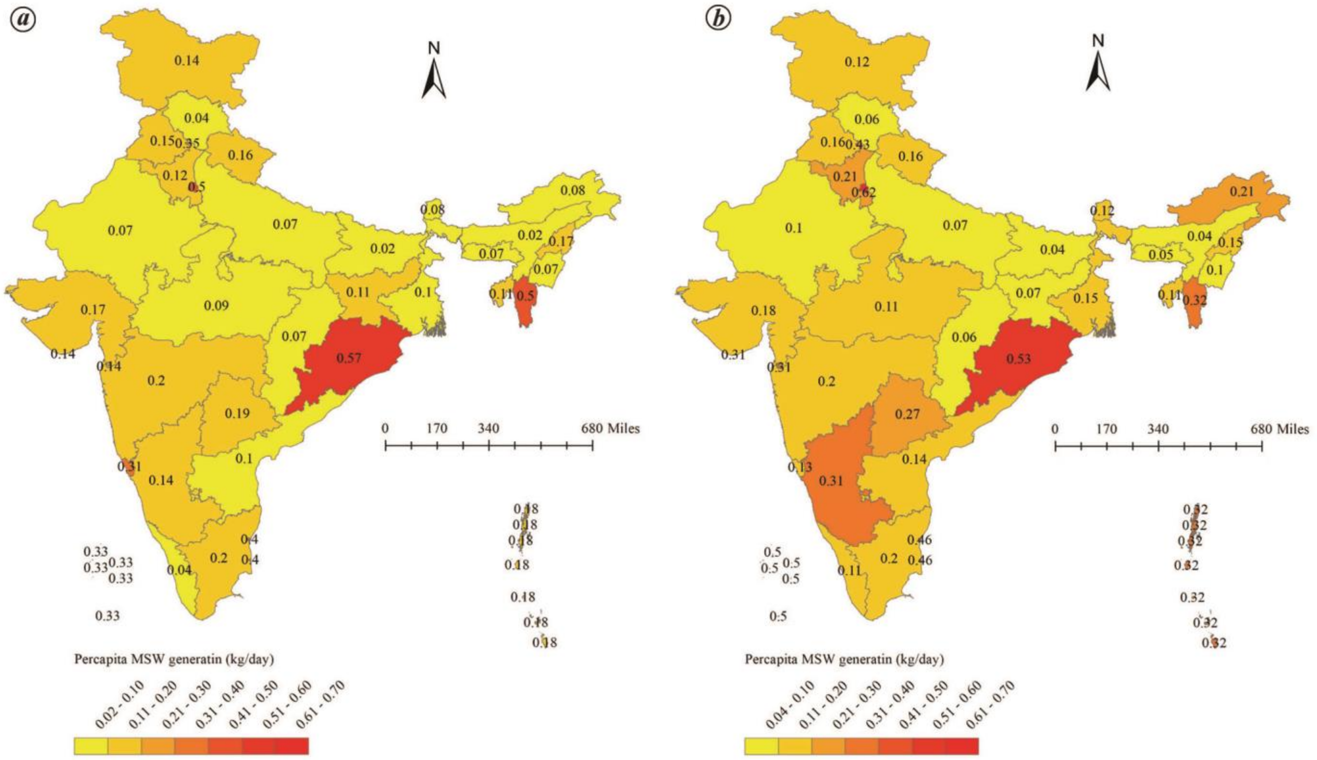

Figure 2. Per capita MSW generation in different states of India during: (***a***) 2014–15; (***b***) 2019–2020.

From Figure 1, it can be observed that the maximum per capita MSW generation of 0.82 kg/day is contributed by Kolkata, West Bengal, and the minimum of 0.03 kg/day by Bengaluru, Karnataka. The per capita MSW generation was calculated as the ratio of waste generation (kg/day) to the size of the population of the city[27].

The per capita waste generation at the individual state level for 2014–15 and 2019–20 was estimated by taking the state-level waste generation data available at Central Pollution Control Board (CPCB) and the 2011 census state-level population data[28]. Figure 2 shows the results for 2014–15 and 2019–20 respectively. The temporal variation

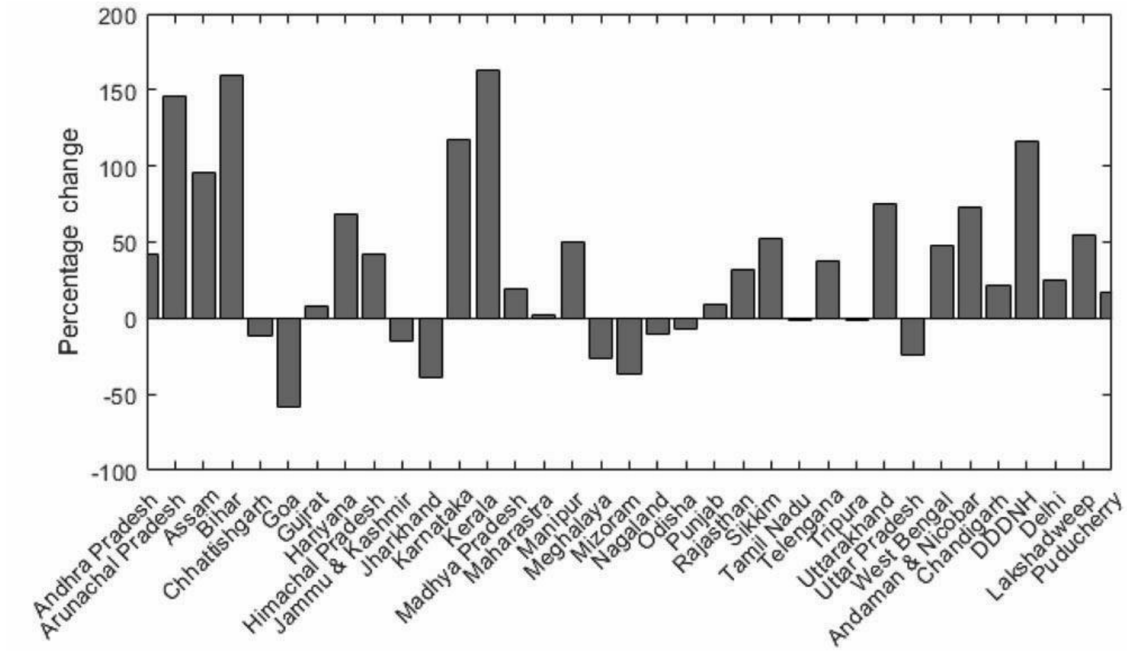

Figure 3. State-wise percentage change in per capita MSW generation from 2014–15 to 2019–20 (Daman, Diu, Dadra and Nagar Haveli, DDDNH).

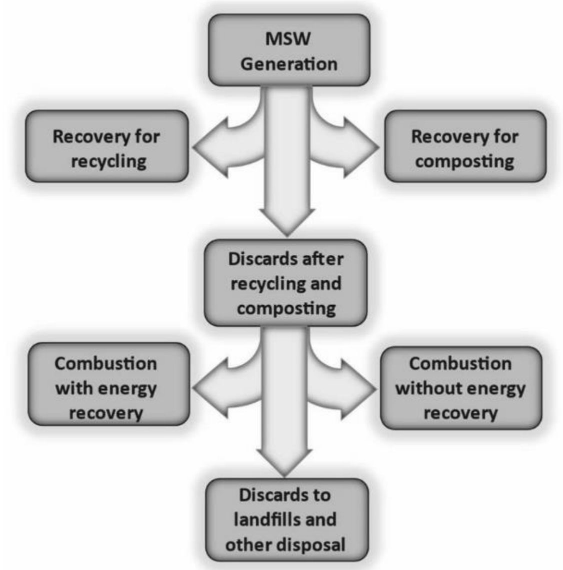

Figure 4. Schematic representation of integrated solid waste management (ISWM)[70].

in per capita MSW generation can be observed clearly by comparing the two figures. A single colour corresponds to a range of values in these figures. The level of per capita MSW generation is also shown for clear observation of the spatial variation in MSW generation.

According to the CPCB Annual Report on SWM 2014–15, the total solid waste generation in India is 141,064 tonnes per day (TPD), while the CPCB Annual Report on SWM 2019–2020, mentions the total solid waste generation in India as 150,847 TPD. The percentage rise in MSW generation is about 07 in 2019–20 from 2014–15. We have estimated the per capita MSW generation during 2014–15 and 2019–20 state-wise, taking the population according to the census data of 2011. From Figure 2, it can be observed that the minimum per capita MSW generation of 0.02 kg/day is contributed by Bihar and Assam, and the maximum of 0.5 kg/day by Odisha, Delhi and Mizoram. From Figure 2, it can be observed that the minimum per capita MSW generation of 0.04 kg/day is contributed by Bihar and Assam, and the maximum of 0.6 kg/day by Delhi. Percentage change in per capita MSW generation from the base year 2014–15 to 2019–20 was estimated (Figure 3). From Figure 3, it can be observed that Kerala recorded a 163% rise and Goa witnessed a 68% decrease in the per capita MSW generation. It gives a clear indication of the change in the total waste generated in 2019–20 compared to 2014–15. It shows that in most states waste generation has increased, while in a few states, it has decreased during 2019–20 as compared with 2014–15.

Integrated solid waste management (ISWM) helps in the generation of waste, recycling of materials, energy recovery and disposal of discards. The objectives of ISWM are to reduce (i) the amount of solid waste, (ii) the associated environmental pollution and (iii) the rate of consumption of the limited available resources[29]. Figure 4 provides a schematic representation of ISWM. MSW once generated goes for recycling, composting and recovery of materials. The remanence or discards after material recovery are sent for combustion without energy recovery and incineration with energy recovery. The rest of MSW after material and energy recovery is sent for disposal at landfills and other disposal sites[30].

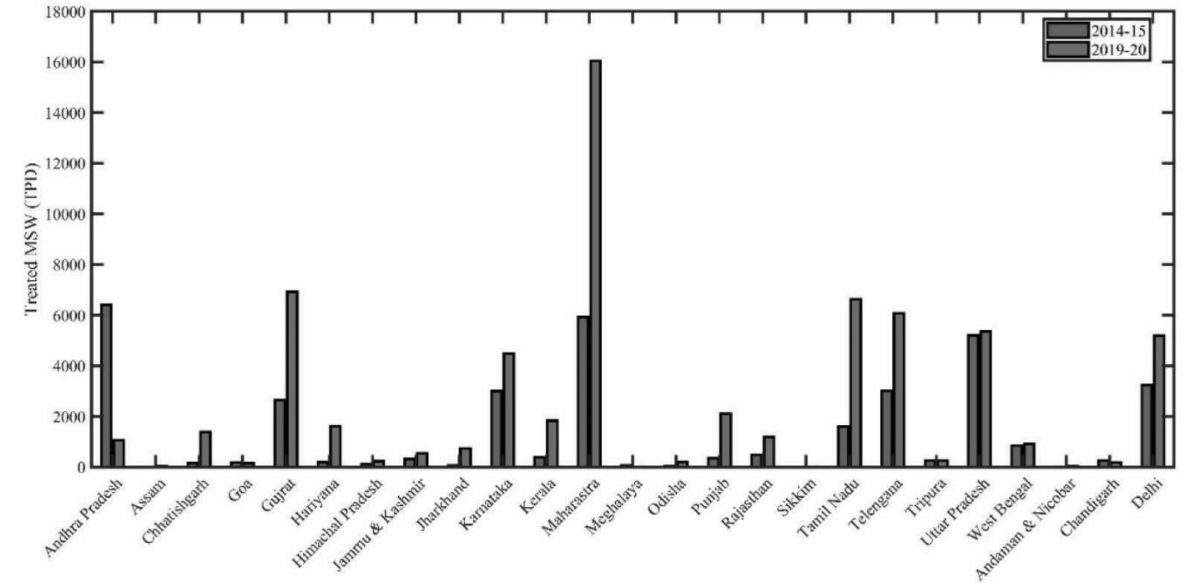

Figure 5. Total treated waste during 2014–15 and 2019–20 in different states of India (source: CPCB Annual Reports 2015–16 and 2019–20).

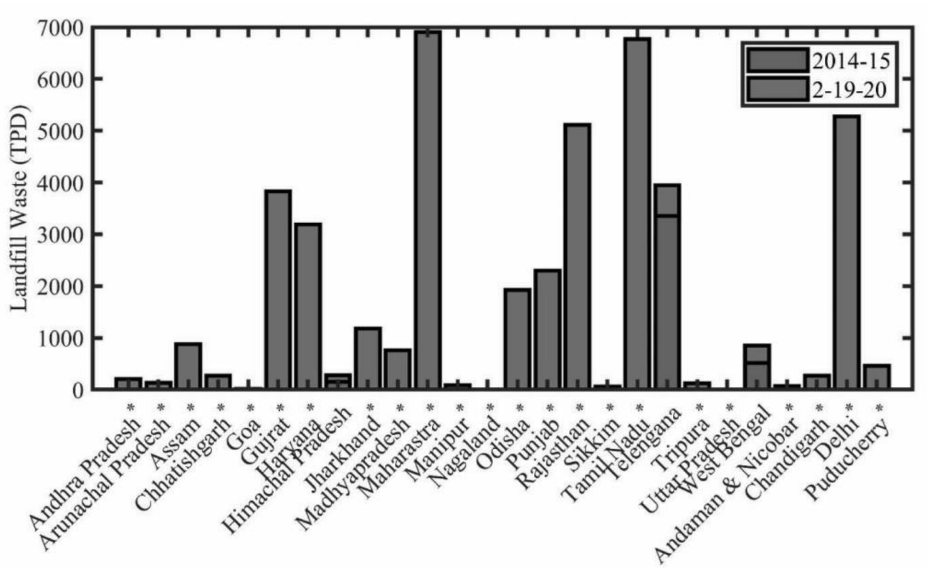

Figure 6. MSW (tonnes/day) going to landfills in different states of India. *These states do not have data for 2014–15.

According to the ISWM protocol, once the waste is generated and collected, the materials are either selected for recycling or composting which is considered as treated waste. Figure 5 presents the amount of treated waste in different states in India during 2014–15 and 2019–20. From the figure, it can be observed that the treated waste (TPD) during 2019–20 is maximum in Maharashtra. In this state, the treated waste amount has increased by 170% from 2014–15. In most of the states, there was an increase in the treated MSW. However, Andhra Pradesh reported a decrease of 504% during 2019–20 from 2014–15 (Figure 5).

House-to-house waste collection is carried out in urban local bodies (ULBs) in India. The collected waste is segregated and transported to the nearest available processing facility, where it is subjected to appropriate process, e.g. composting, vermicomposting, biogas generation, or pelletization, which can be used for refuse-derived fuel (RDF). The discards, after recycling or composting, are sent for combustion either with or without energy recovery in the next stage of ISWM. The remaining discard goes for open dumping or to available landfill sites. In some states, dumpsites are also converted to landfill sites with physical verifications by expert stakeholders.

Figure 6 presents an overview of the quantum of waste that goes to landfill sites in different states, which revealed that Maharashtra tops the list in term of treating the quantum

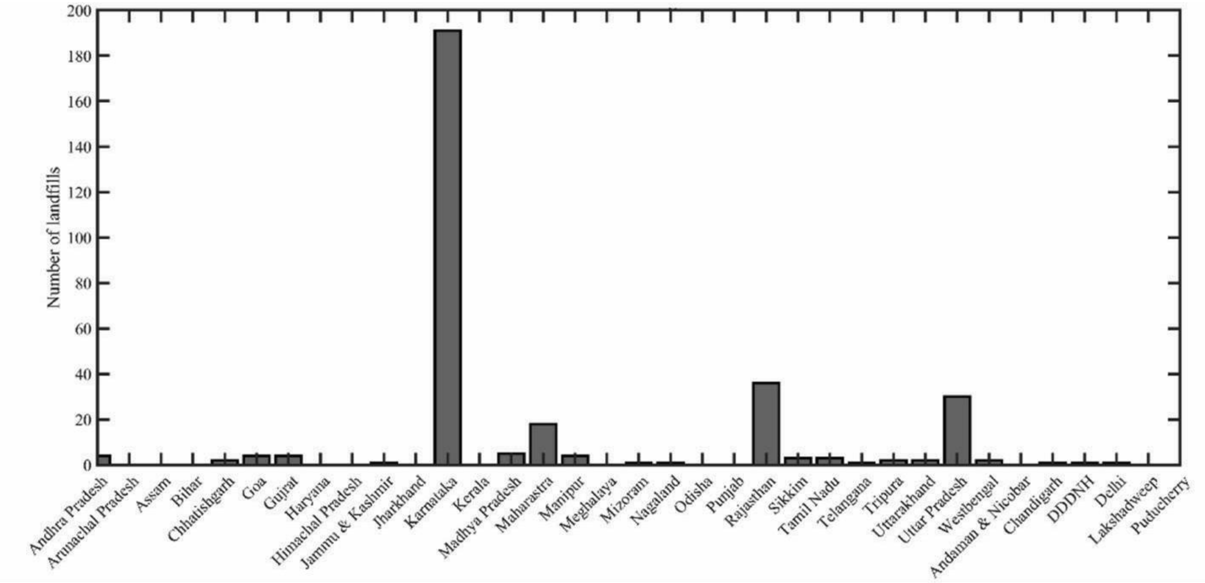

Figure 7. Number of landfills during 2019–20 in India.

of waste through landfilling. Except for Haryana, Telangana and West Bengal, other states had no data for waste treatment through landfilling during 2014–15. Figure 7 shows the number of landfills during 2019–20 in India which shows that Karnataka has the maximum number of landfills as per the CPCB Annual Report 2020.

The state-wise ISWM status was analysed for 2019–20, which included all the 4370 ULBs of India. The CPCB Annual Report 2019–20 reveals that 37% ULBs contribute to material recovery and 6% to energy recovery. Karnataka has the highest number of ULBs with sanitary landfills, and Madhya Pradesh has the maximum number of ULBs with energy recovery (Table 1). Various mass recovery waste management practices include composting and vermicomposting, while energy recovery waste management practices include RDF or pelletization in many ULBs of India[31,32].

Composting is one of the widely used SWM practices all over the country. This is the process of decomposition of organic matter by microorganism[33]. In this composting process, the volume is reduced up to 50% of the original waste[34]. Garbage and sewage sludge can be used in the process of composting[35]. This is the most environmentally sustainable method of SWM, as the byproduct of composting helps in keeping the soil fertility intact, improving the water retention capacity of soil and facilitating in nutrient delivery to plants from the soil[36]. In this process of waste management, the emission of greenhouse gases (GHGs) such as CO_2 and CH_4 is predominant[37]. It has been estimated that from the industrial-scale composting area, the CO_2 and CH_4 emission rates (g per kg of dry waste) are 44 ± 8.6 and 3.0 ± 0.74 respectively[38]. N_2O emission is negligible from the composing process[39]. The environmental factors such as temperature, pH and moisture are the crucial variables in this process[40]. The end-product will contain heavy metals and pathogens[41]. For better results, there should initially be a separation of inorganic and organic materials from the waste stream[42,43].

Vermicomposting is another widely used practice for waste management in the Indian states. It is one of the eco-friendly method of waste management, wherein the decomposition is accelerated by microorganisms in the presence of earthworms[44]. In vermicomposting, a wide range of waste such as agricultural, animal and municipality waste are decomposed at a faster rate as compared to composting[45]. The end-product of vermicomposting has a lower carbon-to-nitrogen (C : N) ratio than composting. Hence the emission of GHGs such as CO_2 and CH_4 is less and N_2O emission is higher in vermicomposting than composting[46]. The vermicompost is known enhance the plant nutrient availability, plant growth hormones and soil aggregation which improve the soil's physical health[47]. The byproduct is mostly used in organic farming. If the temperature rises above the thresholds, the earthworms will die and the environment will be anoxic[48]. The vermicomposts are free of heavy metals, as it is accumulated in the bodies of earthworms[49].

Biogas is the process of anaerobic fermentation of organic waste by certain microorganisms. It is used in heat and electricity generation[50]. The energy produced from biogas is renewable and it is a low GHG emitting system[51]. Biogas can be further upgraded to biomethane, which is used as vehicular fuel and natural gas[52]. Biogas is responsible for the emission of flammable, highly toxic and potentially harmful gases into the environment[53]. It emits air pollutants such as CO, NO_x, volatile organic compounds (VOCs) and SO_x (ref. 54). A combined heat and power unit should be installed for better output from the biogas plant. Biogas has an energy efficiency of 3.33% on average[55]. RDF or pelletization is the process of production of pellets from combustible material in the household garbage to produce energy. It is a technological solution for the disposal of city garbage,

Table 1. Status of integrated solid waste management (ISWM) in operation in states of India during 2019–20

State/Union Territory	No. of urban local bodies (ULBs)	No. of ULBs with composting	No. of ULBs with vermicomposting	No. of ULBs with biogas	No. of ULBs with RDF/pelletization
Andhra Pradesh	110	27	29	7	0
Arunachal Pradesh	2	0	0	0	0
Assam	96	2	0	0	2
Bihar	142	79	1	0	0
Chhattisgarh	168	166	0	0	2
Goa	14	12	0	0	0
Gujarat	170	38	33	3	2
Haryana	86	51	10	1	3
Himachal Pradesh	54	51	0	0	0
Jammu & Kashmir	80	2	2	2	0
Jharkhand	42	22	3	1	1
Karnataka	279	176	48	9	0
Kerala	93	14	7	93	0
Madhya Pradesh	383	100	2	7	83
Maharashtra	394	330	82	41	17
Manipur	27	5	0	0	0
Meghalaya	7	1	0	0	0
Mizoram	3	0	0	0	0
Nagaland	32	0	0	0	0
Odisha	114	0	0	0	0
Punjab	167	167	1	0	2
Rajasthan	193	1	2	0	0
Sikkim	7	3	0	0	0
Tamil Nadu	664	1	2	1	0
Telangana	140	99	99	1	1
Tripura	20	1	1	0	0
Uttarakhand	91	1	1	0	0
Uttar Pradesh	652	14	0	0	2
West Bengal	125	10	0	0	0
Andaman and Nicobar	1	1	0	0	1
Chandigarh	1	0	0	0	0
Daman, Diu, Dadra and Nagar Haveli	3	3	0	0	0
Delhi	5	5	1	5	3
Lakshadweep	0	0	0	0	0
Puducherry	5	1	1	1	0
Total	4370	1383	325	172	119

Source: CPCB Annual Report, 2020.

thus making the environment clean[56]. This process involves drying, separation of non-combustibles, size reduction and pelletization[57]. The energy efficiency of RDF is greater than that of biogas plants[58].

According to the CPCB Annual Report 2019–20, Gujarat, Haryana, Jharkhand, Madhya Pradesh, Maharashtra, Telangana and Delhi employ composting, vermicomposting, biogas and RDF/pelletization as waste management practices. Andhra Pradesh, Jammu and Kashmir, and Punjab practise composting, vermicomposting, and RDF/pelletization processes of waste disposal. Assam and Chhattisgarh practise composting and RDF process of waste management. Goa and Andaman and Nicobar Islands practise composting and biogas methods of waste disposal. Bihar, Himachal Pradesh, West Bengal, and Dadra and Nagar Haveli and Daman and Diu (DNH&DD) mostly practice composting for SWM. Karnataka, Kerala, Jammu and Kashmir, Puducherry and Tamil Nadu practise composting, vermicomposting and biogas methods for SWM. Tripura and Uttarakhand depend largely on composting and vermicomposting methods of SWM.

In some cities and areas, open dumping is prohibited to protect the environment and for public health safety. Hence, landfilling is an option for the safe disposal of waste in such areas. Sanitary landfills are used for the disposal of MSW. The operational phase of a sanitary landfill is organized around the concepts of cells, daily covers and lifts[59]. Each day's waste is received and compacted into cells, which are then covered at the end of the day with a thin layer of soil or other materials[60]. The size of a cell depends on the daily volume of refuse to be buried, but typically it is 3 m (10 ft) thick (including daily cover) and the individual areas are determined by the amount and density of the compacted refuse[61]. Cells are covered each day, or more often, if necessary, to prevent the windblown spread of refuse, to reduce odour, to control the amount of water entering the cells, and to control rodents, birds and flies from accessing the garbage. When a given active area of the landfill is filled with cells, other layers, called as lifts, can be added on the top[62]. The landfills are known to release CO_2, CH_4 and VOCs, and generate leachates[63].

Incineration is the process of burning of all kinds of waste to generate energy. The energy content of MSW depends on the mixture of materials that it contains as well as its moisture content. Khan and Abu-Ghararah[64] have developed an equation to predict the heating value of MSW based on cardboard and paper (*CP*) and food fractions (*F*), plus a term that accounts for plastic, leather and rubber (PLR). The high heating value (HHV, kJ/kg) = 53.5 (F + 3.6 CP) + 372 PLR. If we assume that all the latent heat is lost from the stack during combustion, the net energy derived from the material burned, known as the lower heating value (LHV) can be computed as LHV = HHV – ($2440W – 9H$), where W is the kg of moisture in waste and H is the kg of dry waste with hydrogen[64]. The waste generated in the incineration process is converted to ash, flue gas and heat. This causes air pollution by emitting particulate matter, heavy metals such as lead and mercury, and toxic chemicals such as dioxins[65].

Waste-to-energy is one of the significant components of ISWM. According to the CPCB 2019–20 Annual Report, the total amount of MSW generated is 150,761 TPD, for the entire India, of which 96.8% (145,957 TPD) solid waste is collected, 70,881 TPD (48.56%) of waste is treated and 40,952 TPD (28.06% of total collected waste) is landfilled. The remaining 23.4% is not considered in the data. The report also suggests that there was an increase in the percentage of solid waste processing plants from about 19 in 2015–16 to 47 in 2019–20 in the county. Also, nine waste-to-energy plants are operating in different states in the country (Table 2).

The higher-income countries generate more solid waste, but they deploy new technologies to recycle and treat waste, which helps in the reduction of waste generation and disposal[66]. The limitations in access to resources and technology in developing countries like India leads to higher waste generation and disposal. In developed countries, practising of 3Rs (reduce, reuse and recycle) is the most preferred sustainable approach in SWM[67]. Further, capturing of GHGs at landfill sites and storing them in the soil for use in power generation using appropriate suite of technologies are widely practiced in developed countries[68]. The ash generated from the incinerators contain highly toxic compounds[69]. Thus, utilization and/or application of such ash in different activities should be regulated and/or checked to facilitate healthy environment. Proper care and regulation are essential for the safe disposal of such ash. India should also intensify the 3Rs method of waste management, which need to be incentivised for the ease of adoption by the public. Advanced technologies should be employed to capture carbon emissions from landfill sites into bedrock.

Owing to the pluralistic dimensions, the SWM has become both a challenge as well as an opportunity for public authorities, academicians, researchers and policymakers. The rapid recent urbanization in India has posed challenges in MSWM, and the present analysis provides a succinct view of the status of the MSW generation, treatment and disposal in different states in the 21st century. Kolkata reported the highest per capita MSW generation (0.82 kg/day), whereas Bengaluru reported the lowest (0.03 kg/day) during 1999–2000. Kerala reported a 163% rise and Goa reported a 68% decrease in the per capita MSW generation in 2019–20 from 2014–15. This is suggestive of the fact that most of the Indian states have reported an increase in waste generation has increased during 2019–20 compared to 2014–15, with few exception, e.g. Goa.

ISWM helps in the generation of waste, recycling of materials and disposal of discards. During 2019–20, Maharashtra tops the rank in terms of treating waste, where the amount of treated waste has increased by 170% from 2014–15. In most states, there was an increase in treated MSW, except for Andhra Pradesh, which reported a decrease of 504% during 2019–20 from 2014–15. Maharashtra reported the highest quantum of waste being processed in landfills. Waste-to-energy is one of the significant components of ISWM and nine waste-to-energy plants are operating in the country.

In India, composting and vermicomposting are used for materials recovery; while biogas, RDF/pelletization and incineration are used for energy recovery in most of the ULBs. Out of total 4370 ULBs, 31.6% practice composting, 7.4% practice vermicomposting, 3.9% practice biogas and only 2.7% ULBs practice RDF/pelletization methods of waste treatment. The present analysis is an eye-opener for the decision makers and provide impetus to develop appropriate strategy across the country, owing to its diversified cultural and behavioural practices.

Table 2. Operational waste-to-energy plants in India

State/Union Territory	No. of plants	Total power generation (MW)
Delhi	3	59
Uttar Pradesh	2	5
Tamil Nadu	2	58
Maharashtra	1	4
Madhya Pradesh	1	11
Total	9	137

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Correction

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The name of the reviewer of the book should read as Rohini Mattoo and not Rohini Matto.

– Author