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Review

Solid Waste Management in India: A State-of-the-Art Review

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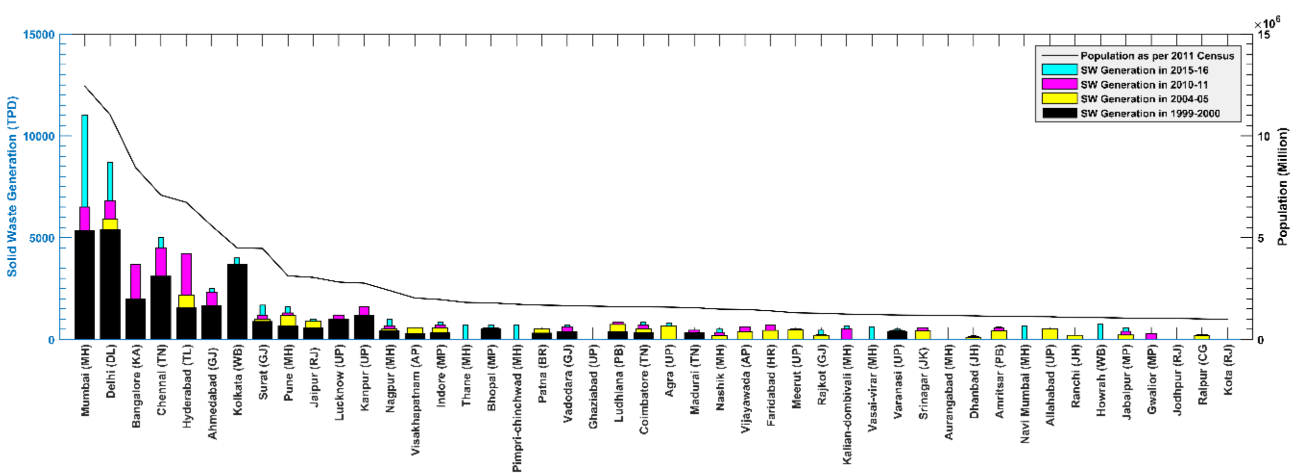
ABSTRACT

This paper presents the current scenario of solid waste management aspects and its challenges in India, which will benefit developing and low-income countries. The leading cause of waste generation is the growing population and the new lifestyle due to the increased per capita income. Consequently, the magnitude of solid waste is continuously growing along with its compositional diversity. In earlier days, the wastes were organic and could be disposed of in low-lying areas conveniently without causing any adverse impact on the environment. But today, the organic fraction of waste has steeply declined while the inorganic portion has increased manifold. Moreover, wastes from industries, hospitals, construction sites, households, and many other sources severely affect the environment and public health. Also, the chemicals generated from the improper disposal of these wastes enter the air, soil, and water resources, causing hazardous and toxic effects in countries that could not implement the adopted policy framework strictly. A state-of-the-art review is conducted in this paper to further search other primary and prevalent reasons behind the inability of proper waste management and to find a real solution.

Keywords: Challenges, Municipal solid waste, Solid waste management, State-of-the-art review, Waste characterization, Waste generation

Graphical Abstract



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1. Introduction

The improvement in people's living standards because of the industrial revolution and economic development has entirely changed their consumption patterns. But simultaneously, it has created extreme complexity in solid waste management (SWM). This altered lifestyle has brought a tremendous increase in the share of the inorganic constituents in the wastes, due to which the SWM has been severely affected and has become a global problem today [1,2]. Presently, the waste disposal scenario has become a considerable threat compared to earlier times when the waste was primarily organic and could be safely disposed of in low-lying areas, assimilating into the natural biogeochemical cycles [3]. Moreover, the rapid increase in industrially-manufactured materials such as metals, glass, plastics, papers, rags, and polystyrene has enhanced the share of inorganic wastes [4]. It has brought several new solid wastes, such as municipal solid waste from fruit and vegetable markets, gardens and parks, drain silt and street sweepings from the domestic areas, commercial sectors, and common spaces [5-9]; construction and demolition waste from stones and bricks, reinforcement steel, and infrastructure-building activities [10-12]; biomedical waste from used/expired drugs and medical instruments, tissues and organs generated from healthcare and veterinary establishments [13-15]; E-waste generated from the disposal of end-of-life electronic equipment [16]; industrial waste from various industrial manufacturing centers [17-20]; special waste toxic and hazardous wastes from households, and trading zones [21-23]. The significant causes of the rise in these manufactured materials are the expanding urban areas, rising consumerism, and the exponentially growing population and their varying activities. These factors not only affect a particular area or a country but also have made solid waste generation (SWG) a worldwide problem [24-27].

Almost all the countries of the World are undergoing an intense struggle but still have failed to find a proper and effective solution to manage waste. However, a few developed countries like Germany, Italy, Canada, and Australia have effectively addressed this issue. But the rest of the World, including numerous developing and under-developed countries, is still establishing the basic infrastructure, let alone managing solid waste. Therefore, this paper extensively reviews the work done globally in this field and finds a feasible solution to India's SWM condition. A practical solution for managing solid waste in India can lead the developing and under-developed countries of the World, as India shares 17.5% of the World's population and is the 2nd most populous country. Moreover, India has more than 1.4 billion people spread over 3.3 million sq. km, approximately 2.4% of the World's terrestrial area.

In addition to the introduction given in Section 1., the rest of the paper is organized as follows - Section 2. presents a criteria-based state-of-the-art review of the solid waste management processes employed in India along with an outlook of solid waste management practices globally; Section 3. deals with the present scenario of solid waste management including the framework of MSWM, the trend of waste generation in various cities, the composition of waste, it also discusses the status of waste processing undertaken in India; Section 4. discusses the key challenges and tries to find solutions for an efficient solid waste management paradigm in India; Section 5. presents the detailed conclusion, and the References are given at last in the paper.

2. State-of-The-Art Review on Solid Waste Management

The state-of-the-art review presented in this paper tends to address more current matters in solid waste management in contrast to other combined retrospective and contemporary literature along with new perspectives on SWM and points out areas for further research, as depicted in the tables below. In order to have better clarity and to grasp the matter at a glance, the significant contribution of each study is concisely and precisely presented year-wise/criteria-wise/country-wise in Table 1., Table 2., and Table 3., along with a short description of gaps and novelty.

A decadal highlight of literature presented in Table 1. points toward increasing population, urbanization, industrialization, and improvement in the standard of living as factors behind increasing solid waste generation. Recent advancements in solid waste direct administrative attention toward the role of public-private partnerships. It identifies numerous blockades to effective MSW management. It shows that even small steps, such as segregation at source, can significantly determine the feasibility of employing waste-to-energy plants. This may reduce greenhouse gas emissions and provide sustainable logistics and waste transport solutions. Modelling resources and wastes considering their lifecycles is another holistic way to determine their reusability and potential for recycling and material recovery. Implementing a systems approach in MSWM will consider not only the individual components but also their interaction, their effect on the environment, and that of the environment on the MSWM system. Application of geographically and topographically relevant technology based on the existing condition of an area can efficiently optimize, considering the MSW management processes as a system. It may benefit the management agencies to form better policies, solve imminent and long-term issues, and improve the health of the environment.

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Table 1. A summary of research paper studies that covered solid waste management

Year	Highlights	Ref.
2022	Proper engagement of the private sector in SWM can create sustainable circumstances. Education and awareness are crucial for household waste management and new approaches.	[28]
2021	The life cycle approach can close the gap between solid waste management in metropolitan and regional cities. And waste-to-energy significantly reduces GHG emissions and particulate matter.	[29]
2020	The fuzzy Delphi method identified 146 barriers to attaining sustainable SWM. The most significant ones are household hazardous waste, inadequate research capital, local architecture, lack of staff capability, and standard processes.	[30]
2019	A strong correlation exists between geographical position and economic status with waste characteristics. It also undertakes LCA models to select appropriate waste management algorithms to evaluate and find a sustainable solution.	[31]
2018	The rapid increase of solid waste is due to population increase, urbanization, rapid industrialization, and economic sustainability.	[32]
2017	The model was generated utilizing TOPSIS in the GIS environment to develop a suitability indicator for siting the units to minimize fixed and transportation costs and maximize the system's suitability.	[33]
2016	Greenhouse gas emissions could be reduced by applying the proper framework of SWM, such as waste-to-energy and material recovery, instead of landfilling.	[34]
2015	Systems engineering approaches such as systems engineering, industrial ecology, integrated solid waste management strategies, integrated systems planning, design and management, and uncertainty analysis shall be applied to SWM.	[35]
2014	Multiple methods for decision-making regarding waste management suggest direction by mass-balance approach, goal-oriented evaluation, and transparent and reproducible presentation of the methodology, data, and results.	[36]
2013	Urbanization, economic growth, inequality, institutional issues, governance, policy, international influences, and cultural and socio-economic aspects are the factors that have complicated the SWM in developing countries.	[37]
2012	All the SWM aspects shall be examined for health and safety, environmental issues, and disaster-prone/affected areas.	[38]

Table 2. A criteria-based summary of recent solid waste management studies

Study Criteria	Objective and key findings
Management	Waste management systems must be continually improved; waste diversion indicators analyze waste management and create a framework and an easy-to-use metric for improving waste management efficiency [39]. Innovation in SWM shall extend to product, organization, and process innovation in the disposal segment [40].
Framework	Creating avenues for the circular economy through recovering and recycling materials from solid waste, similar to the developed countries, may help achieve climate change and sustainable development goals [41]. Literature finds that clear laws, regular public campaigns, and fee methodology are pillars of effective SWM [42]. Also, as involvement in social community activities, education level, and per capita expenditure [43].
Awareness	Public perception and willingness to pay for solid waste management have been highlighted as significant impediments to the effective collection, segregation and processing of solid waste [44,45]. A unique study aimed at raising awareness of SWM through formal education and gauging the gap in knowledge and attitude of students and teachers revealed that students have a positive attitude and high understanding of environmental issues. In contrast, there is a gap in teachers' practical knowledge and education to implement SWM [46].
Generation	The waste generation shall be studied along with analyzing economic, social and population indicators [47]. In addition to the inherent difficulties in MSWM operations, infrastructure, finance, and improper implementation of policies are among the significant challenges in SWM in India [48]. Another study finds a correlation between geographical position and economic status with waste characteristics. It also undertakes LCA-based models to select appropriate waste management algorithms to evaluate and find a sustainable solution [31].
Collection	The relation between distance travelled, working time, and waste collection system can be used to improve the solid waste management system, develop an effective solid waste collection system, and optimize the map of recycling stations in urban settings [49]. Clustering is also one of the potent optimization modelling to enhance solid waste collection [50]. These can provide appropriate collection plan, route map and usage of geo-positional attributes for optimal routing and improved efficiency and offers significant savings in time, labor, and pathways.

Table 2. Continue

Study Criteria	Objective and key findings
Segregation	Multi-criteria decision analysis aimed at assessing and comparing the sustainability of different waste management schemes finds that a door-to-door collection system (efficiency>80%) is far better than point collection (efficiency=35%) in the segregated collection of waste [51]. Internet-of-Things has found its application in detecting the variation in relative humidity in the presence of wet waste, helping to monitor waste bin status regularly [52].
Characterization	Waste broadly includes plastics, paper, diapers, LDPE, plastic bags, glass, pharmaceuticals, and organic material [53]. Organic waste constitutes the primary category (57%) at pilgrimage events, indicating energy conversion potential [54]. Several pieces of literature signify characterizing as the first step to a successful SWM. Artificial intelligence and machine learning approaches can investigate the impact of seasonal variation on the characterization of MSW [55].
Minimization	Life-cycle analysis of hospitality solid waste management can result in cost avoidance, enhance consumer image and employee morale, and reduce environmental impacts [56]. Open dumping of the increasing MSW in Thailand has led to various problems associated with solid waste, including the emission of greenhouse gas. A report intends to ascertain the influencing factors and ways to reduce the per capita generation of MSW [57].
Storage	The location of solid waste storage based on the number of stations, maximum walking distance, and container capacity improves waste storage services [58]. The storage capacity of landfills can be effectively increased by increasing storage height, but it can cause leachate-induced slope instability [59].
Transport	Vehicle routing optimized for travel duration and path strengthens the triple bottom line of sustainability and improves the solid waste management framework [60]. Another study points out that with no marginal increase in cost, the transportation model based on locational planning of MSWM systems shows considerable savings in CO_2 emission [61].
Treatment	Composting is an economical, sustainable, and environmentally benign alternative for treating organic constituents [62]. A study develops a multi-objective optimization model to select optimum technological solutions for MSW; with the help of this decision support system, sludge co-processing can be promoted for managing solid waste [63].
Recycling	Stone-cutting waste can be recycled as a feasible replacement for aggregates in construction, concerning cost reduction in storage and disposal [10]. Several countries are striving hard to inculcate a culture of recycling in the day-to-day life of people and reduce the magnitude of solid waste reaching open dumping sites.
Disposal	High concentrations of heavy metals such as Cu, Mn, Fe, Cr, Pb, Co, Zn, and Ni in groundwater near waste dumping areas. Advances in disposal technology, such as bioreactor landfills and improved liner materials, may help prevent contaminants in the environment [64]. The prevalence of open burning, dumping, management, treatment and disposal of solid waste in Bangladesh has also been documented [65].
Impact	Using artificial intelligence to gauge the temporal variation in waste characteristics can help predict and reduce the impact of MSW by incorporating early sustainable waste management decisions [55]. The presence of odorous compounds causes severe nuisance near and around MSW processing facilities due to the organic wastes' high moisture content and perishability. After that, aromatic and halogenated hydrocarbons have carcinogenic risks [66].
GHG Emission	Sustainable circular waste management systems may contribute considerably to alleviating climatic heating by reducing the emission of GHGs [67]. The Integrated SWM approach results in the maximum reduction of GHG emissions compared to the recycling and incineration approaches [68]. Composting has been the best scenario for the least GHG emission, whereas landfilling generated the most GHG, followed by open burning [69].
COVID-19	The recent COVID-19 pandemic has put massive pressure on solid waste management with its peculiar biomedical waste. An enormous instability has been inducted into healthcare waste handling, recycling, treatment, and disposal [70]. It has been found that the SARs-COV-2 virus, responsible for COVID-19, has more than 72 hrs. of stability on plastics and steel compared to copper or cardboard [71]. The wastes produced during this period are bio-hazardous and highly undesirable.
Waste-to-energy	Estimating methane emissions and technical know-how for initiating landfill gas projects to extract energy needs to be developed along with developing novel technologies for enhancing the energy content of waste. Along similar lines, an article finds a novel approach for WTE by converting solid waste plastics into graphene nanosheets to create high-performance supercapacitors [72]. An assessment links WTE resource potential to an area-based prioritization framework for better performance [73]. Another article proposes the recovery of waste and energy generation and urges the public authorities to invest more in WTE technologies to contribute to sustainable development, economic growth, and ecological and environmental well-being [74].

optimize, considering the MSW management processes as a system. It may benefit the management agencies to form better policies, solve imminent and long-term issues, and improve the health of the environment.

Table 2. presents a criteria-based summary of solid waste management studies undertaken in the past five years. This categorical review informs the objectives and key findings in research areas that require more focus in the present times. It reveals that modern methods of continuous improvement of the management system and holistic innovation through product, organizational, and process innovations may fill the gap in the management of solid waste. Advancing into a circular economy framework, a country benefits by alleviating pressure on the environment and promoting sustainable development. It also increases competition and stimulates innovation in the field. The concept of a circular economy has the potential to boost the economic growth of a nation and save time, resources, and adverse environmental impacts.

Similarly, the inclusion of socio-economic factors such as society, literacy rate, and awareness by public campaigns play a crucial role in improving solid waste management. Yet, few consider the economic and social indicators, along with population indicators. This increases the gap between the theory and practice of MSWM, causing inadequacy of infrastructure and finance. Moreover, the influence of geographical location and economic status on the changing solid waste characteristics remains unknown.

2.1. Solid Waste Management Worldwide Outlook

The various studies [3,25,27,75,76] conducted to determine the trend of SWM worldwide show that the SWG increases following the economic advancement of countries from low-income to high-income. Based on the data from a World Bank Report conducted on 192 countries [76], the statistical correlation of SWG

Table 3. A summary of solid waste management studies done in various countries

Year	Criteria	Issue addressed	Place	Country	Economic Status	Ref.
2022	Awareness	Willingness-to-pay	Hawassa	Ethiopia	LI	[44]
2022	Characterization	Variation of waste characteristics	Johannesburg	South Africa	UMI	[55]
2022	COVID-19	Emerging issues in SWM	Luzon, Visayas, Mindanao	Philippines	LMI	[77]
2022	Impact	Impact assessment using multispectral imagery	Yenagoa, Bayelsa State	Nigeria	LI	[78]
2022	Minimization	Factors for reducing solid waste	Shanghai	China	LMI	[57]
2021	Characterization	MSW Composition Analysis	Nur-Sultan City	Kazakhstan	UMI	[53]
2021	Collection	Efficiency of collection	Mexican Municipalities	Mexico	UMI	[79]
2021	COVID-19	Effect of COVID-19 on SWM	Brazil	Brazil	UMI	[80]
2021	Framework	Life cycle assessment for MSW management	New South Wales	Australia	HIC	[81]
2021	Framework	SWM at Ajmer, India	Ajmer, Rajasthan	India	LMI	[15]
2021	GHG	Air pollution due to MSWM	Accra	Ghana		[82]
2021	Management	Agent-based modelling for eco-effective SWM	Norte Pioneiro	Brazil	UMI	[83]
2021	Management	Input-output indices for SWM quantification	Nova Scotia, Saskatchewan	Canada	HIC	[39]
2021	Management	Implementation analysis of SWM	Ludhiana, Punjab	India	LMI	[84]
2021	Management	Life cycle cost analysis of MSWM	Mumbai, Maharashtra	India	LMI	[85]
2021	Management	Management of SW at dumpsites	Ibadan	Nigeria	LI	[86]
2021	Management	SWM at Papua New Guinea	Lae City	Papua New Guinea	LMI	[20]
2021	Recycling	Residential solid waste recycling	Annaba	Algeria	LMI	[87]
2021	Segregation	Segregation at source and separate collection	Hoi An	Vietnam	LI	[49]
2021	Treatment	Composting of organic waste	Al-Karak	Jordan	LMI	[62]
2021	Waste-to-energy	Solid waste fuel pellets	Newai, Rajasthan	India	LMI	[88]
2020	COVID-19	Effect of SWM on COVID-19 spread	South Africa, Egypt, Morocco, Algeria, Nigeria, Ghana, Cameroon, Guinea, Ivory Coast, Djibouti, Senegal, Tunisia, Niger, Burkina Faso, DR Congo	Africa	UMI, LI	[89]

Table 3. Continue

Year	Criteria	Issue addressed	Place	Country	Economic Status	Ref.
2020	Framework	Community participation for effective SWM	Jakarta	Indonesia	LMI	[43]
2020	Minimization	Cost minimization	Ankara	Turkey	UMI	[61]
2019	Collection	Efficiency of collection	Bharatpur	Nepal	LI	[90]
2019	Framework	Applying sustainability to MSWM	Mata de São João	Brazil	UMI	[91]
2019	Framework	Mathematical modelling for MSWM	Istanbul	Turkey	UMI	[92]
2019	Management	Community-based SWM	Nkulumane Suburb, Bulawayo	Zimbabwe	LI	[93]
2019	Waste-to-energy	WTE at South Africa	Johannesburg	South Africa	UMI	[74]
2018	Collection	Impact of tourism on waste collection	Italian Municipalities	Italy	HIC	[94]
2017	Characterization	Evaluation of SWM	Mohali & Panchkula, Punjab	India	LMI	[95]
2017	Characterization	MSW Composition Analysis	Kerbala	Iraq	UMI	[54]
2017	Characterization	Waste generation & composition	Lagos	Nigeria	LI	[96]
2017	Management	Biomedical waste management	Francistown, Gaborone, Selebi Phikwe, Lobatse, and major villages	Botswana	UMI	[97]
2017	Management	Multi-dimensional modelling for integrated SWM	Tehran	Iran	LMI	[33]
2016	GHG	Greenhouse gas emissions from landfills	Delhi	India	LMI	[98]
2016	Waste-to-energy	WTE and recycling value	Lahore	Pakistan	LI	[99]
2015	Generation	Public perception hazards of MSWM	West Bank, Gaza Strip	Palestine	LMI	[100]
2014	Disposal	Impact of landfilling on groundwater	Kolhapur, Maharashtra	India	LMI	[101]
2014	Framework	MSWM system in a developing country	Dhaka, Chittagong, Khulna, Rajshahi, Barisal, and Sylhet	Bangladesh	LI	[102]
2014	Framework	SWM and Agenda 21 in Brazil	Brazil	Brazil	UMI	[103]
2014	Management	SWM at Nairobi	Nairobi	Kenya	LI	[104]
2013	Awareness	Willingness-to-pay	Kolkata	India	LMI	[105]
2013	Characterization	MSW Composition Analysis	Beijing	China	LMI	[106]
2013	Disposal	Route Optimization for MSW disposal sites	Gondia, Maharashtra	India	LMI	[107]
2013	Management	SWM at Delhi, India	Delhi	India	LMI	[108]
2012	Awareness	Education and Awareness	Universiti Kebangsaan Malaysia	Malaysia	UMI	[109]
2012	Generation	SWM at Bahrain	Kingdom of Bahrain	Bahrain	HIC	[110]
2012	Impact	Landfill fires and their impacts	Lagos	Nigeria	LI	[111]
2012	Recycling	Recycling solid waste	Delhi	India	LMI	[24]
2012	Recycling	Sustainability in SWM	Gianyar	Indonesia	LMI	[112]
2011	Transport	Collection route using GIS	Nagpur, Maharashtra	India	LMI	[113]
2010	Awareness	Health issues of workers	Cairo	Egypt	LMI	[114]
2010	Awareness	Segregation at source	Mercato San Severino	Italy	HIC	[115]
2009	Disposal	Impact of disposal	Ado-Ekiti	Nigeria	LI	[116]
2008	GHG	Greenhouse gas emissions from MSWM	Chennai, Tamil Nadu	India	LMI	[117]
2008	Management	SWM at Karlsruhe City, Germany	Karlsruhe City	Germany	HIC	[118]
2007	Framework	Optimizing Integrated solid waste management in India	Mumbai, Maharashtra	India	LMI	[119]
2007	Minimization	SWM and disposal emission inventory	Bangkok	Thailand	LMI	[120]

was determined with the urban population and the total population of both urban and rural areas. It was found that the statistical correlation of the quantity of waste generated with the entire population was 0.6390, while that with the urban population was 0.8421. It shows that the statistical correlation with the urban population is nearly 1.5 times more than that of the total population. These figures demonstrate a notable trend of SWG, which increases with the countries' affluence. Still, the measures undertaken to improve the SWM are not up to the mark required for properly disposing of the increased SWG. A summary based on different criteria and issues of the SWM adopted by various countries is shown in Table 3. The economic condition of the nations, such as low-income (LI), low-middle-income (LMI), upper-middle-income (UMI), and high-income countries (HIC), is also shown in this table.

3. Solid Waste Management in India

The present rate of SWG in India is 0.34 kg per capita per day, which is expected to reach up to 0.7 kg per day by 2025 [76]. However, this SWG rate is much lower than nearly 90% of countries worldwide. But, due to the massive population, the total waste generated in India is more than 168,403.24 TPD, because of which India ranks seventh globally in SWG [121]. But it is forecasted that by 2025, India may become a more significant waste generator than Germany, Japan, and Brazil, which are now at the 4th, 5th, and 6th rank, respectively [76]. The SWG will still increase in India because the linear projections show that India's population may grow to 2.6 billion in 2051, as presented in Fig. 1. The urban population's present growth rate is 31.45%, which may increase to 36% in 2051. In contrast, the rural population is 17.97% [122]. Moreover, the total number of urban agglomerations (UAs) and towns may rise to more than 10,000 from 6166.

3.1. SWM Framework

The Central Pollution Control Board and the State Pollution Control Boards/Committees impart environmental policy, pollution monitoring, and reporting at the central and state government levels. Municipal agencies/cantonment boards implement plans and rules in the areas under their jurisdiction at the local level. They also develop infrastructure for collection, segregation, transportation, storage, treatment and processing, and solid waste disposal. India's Municipal Solid Waste (Management and Handling) Rules assign citizens the duty to segregate waste at household levels. It also gives strict adherence to avoiding littering streets and delivering waste through the established delivery system notified by the civic bodies [123]. The SWM model followed in India was simplistic and rudimentary. But, the recent integration of ideas such as reduce, reuse, and recycle (3R) and material and energy recovery has significantly improved the model, as observed in developed countries [26,118,120,124-127].

3.2. Solid Waste Generation

Out of 28 states and 8 union territories (UT) of India, about 50% of its solid waste is generated by only five states/UT - Maharashtra, Uttar Pradesh, West Bengal, Gujarat, and NCT of Delhi. Generating more than 23000 TPD of solid waste, Maharashtra stands at the top, followed by Uttar Pradesh and West Bengal, with SWG of about 15,000 TPD each. States such as Andhra Pradesh, Delhi, Gujarat, Karnataka, and Tamil Nadu create more than 10,000 TPD.

Fig. 2. shows the trend of SWG in India. Moreover, the more affluent the economy of a particular state/UT, the more substantial waste is likely to be generated. Maharashtra generates the highest amount of solid waste of all states and collects 99.3 % of its solid waste. It also utilizes more than 53% of the collected waste for composting, recycling, and energy recovery. The remaining 47% of waste is sent to landfills. Arunachal Pradesh, Chhattisgarh, Karnataka, Manipur, Nagaland, and Puducherry collected around

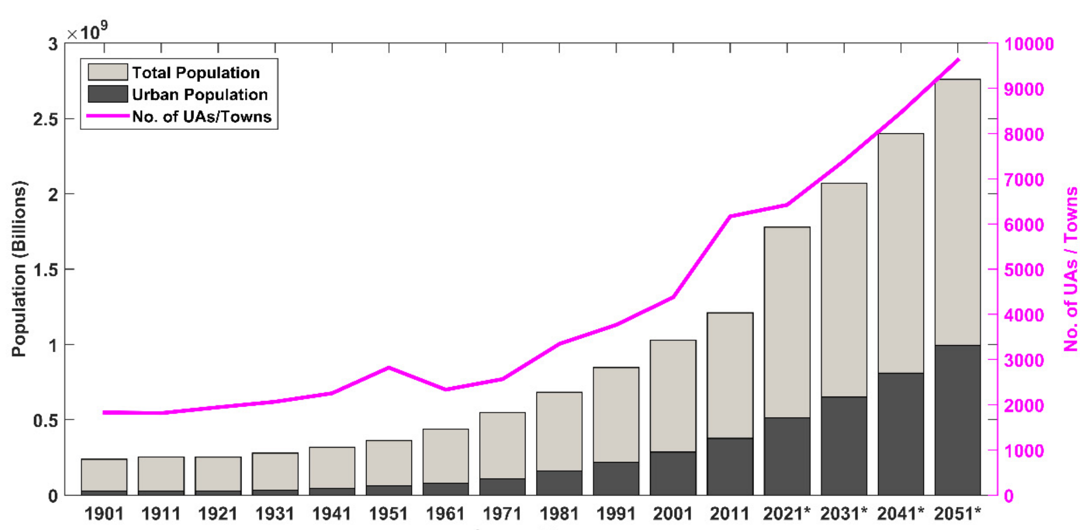

Fig. 1. Trend of growth of UAs/Towns (on the right y-axis) and urban population (on the left y-axis) in India for census years 1901-2011 [122] with linear projection till 2051.

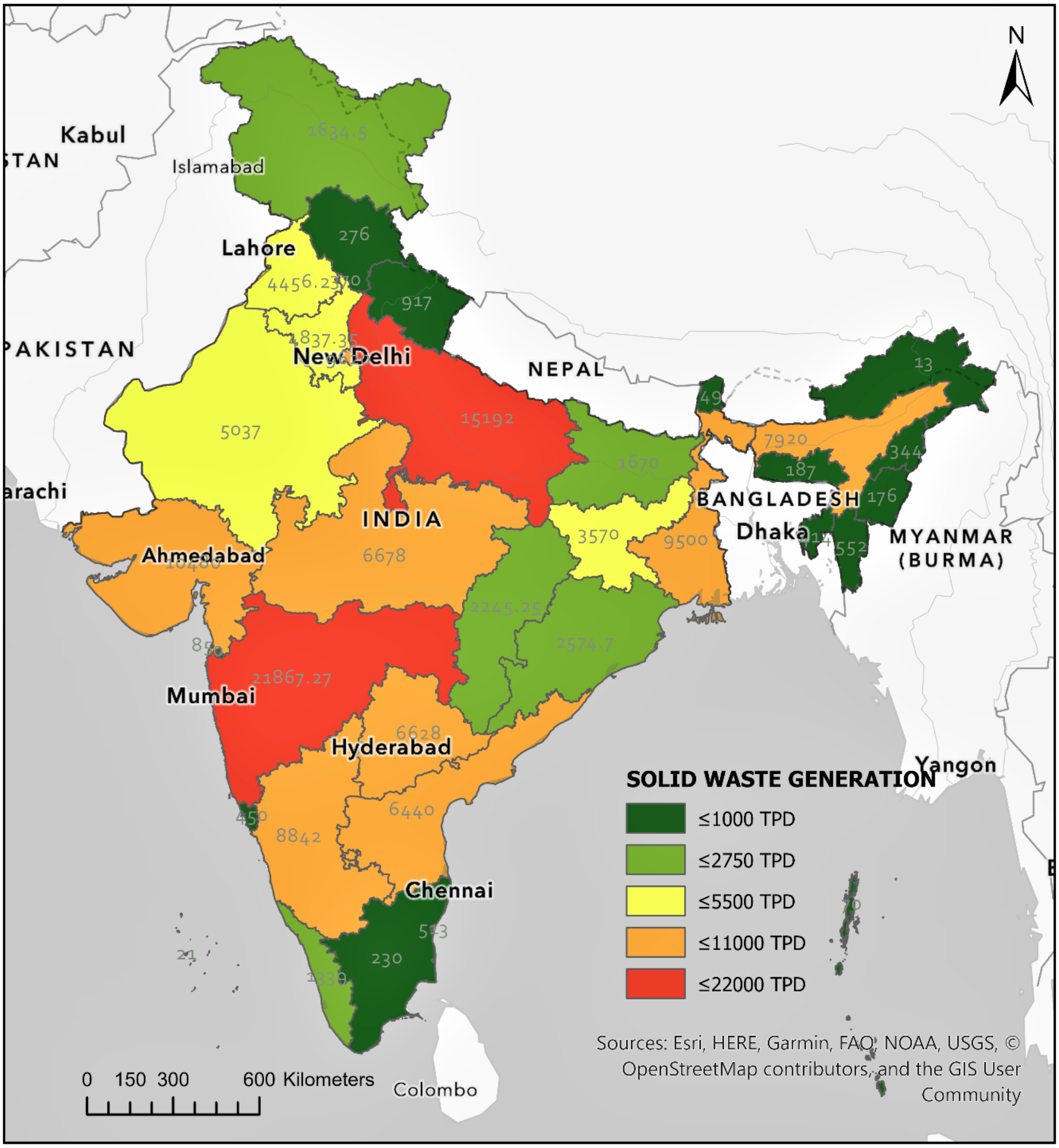

Fig. 2. Solid waste generation trend in India

80% of the solid waste generated and treated only 25% of waste. Mumbai and Delhi produce more than 11,000 TPD of solid waste at the city level. Only about 50% of solid waste is treated, and the remaining 50% finds its way to landfills. Both mega-urban centers lack sanitary landfill facilities and rely on open dumping of solid waste [108]. From 2009 to 2012, India produced 127485.107 TPD of solid waste at 0.17 to 0.76 kg/capita/day for Tier I, II, and III Indian cities [34,123,128]. According to the World Bank, the average per capita waste generation is approximately 0.35 to 0.4 kg/capita/day [76]. SWG increased by nearly 50% from 2001 to 2011 [129].

Fig. 3. in the grouped column and line chart shows the magnitude of SWG for 1999-2000, 2004-05, 2010-11, and 2015-16 in tons per day (TPD) by urban centers of India on the primary y-axis (on the left side). It also compares the trend with the cities' populations in millions, scaled on the secondary y-axis (on the right). It establishes the relationship between SWG and people. SWG has been increasing consistently since yesteryears, with metropolitans such as Mumbai and Delhi leading in waste generation due to their enormous population, immigration, and varied economic activities. Kolkata and Bengaluru have rigorously controlled their SWM as waste generation has increased marginally from 1999-2000

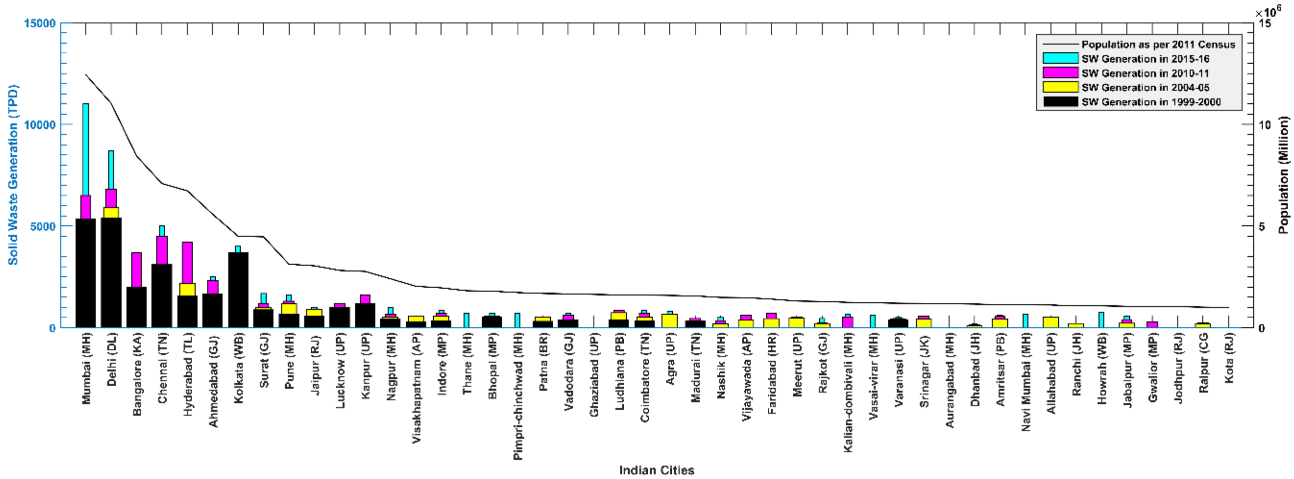

Fig. 3. Solid waste generation by Indian cities [122]

till 2015-16. Summarizing the magnitude of solid waste generated by cities classified based on their economic status as Tier I, II, and III cities present a consistent trend in the solid waste generated by cities of various economic classifications. SWG directly relates to a city's financial state [25]. The city's economic condition: more is the quantity of solid waste generated. Mumbai & Delhi leads the Tier I cities by producing more than 7000 TPD and more than 11500 TPD in 2016. Amongst Tier-II cities, Chandigarh generates the highest quantity of waste. Cities that generate more than 7000 TPD, i.e., Greater Mumbai and Delhi, lack sanitary landfilling facilities [130]. The population growth rate of urban zones is around 36.45%, which is more than twice the population growth in rural areas (17.97%) [122]. Fig. S1. presents the relationship between quantity of solid waste generated by Indian Cities vs their population graphed using curve fitting with 95% confidence bounds. This relation can be developed into a linear model as shown in Eq. (1).

$$Q_{SWG} = 393.2 \times P - 111.2 \qquad (1)$$

where,

Q_{SWG} = quantity of solid waste generated in TPD,
P = population of a city in millions.

3.3. Waste Composition

India's solid waste differs significantly from Western countries in its composition and hazards. The physical composition of India's solid waste on a wet-weight basis includes (a) biodegradable organic fraction (51.3±8.3%), (b) recyclables up to 17.48±5%, (c) the ash content of 30-40%, (d) paper about 3-6%, and (e) inert such as glass, plastic, and metals up to1-6% [128]. Characteristics of waste from 59 Indian cities classified based on population, as shown in Table 4., ascertain the value of the carbon-to-nitrogen ratio (C/N) of 31.91±26.68 low, the moderate calorific value of 1751.20±782 kcal/kg [34,128]. Waste is often attributed to a moisture content of 46.76±13%, making the waste less feasible for energy recovery. High-income cities tend to produce more inorganic waste than organic ones. Solid waste from Tier III cities, i.e., the low per capita income cities, has higher calorific value waste than other towns [34]. Hence, as a town gets economically advanced, the organic share of the waste reduces—consequently, the paper and plastic component increases, which points toward consumerism in the urbanized areas.

3.4. Status of Waste Processing

3.4.1. Waste minimization, recycling, and reuse

In India, an extensive informal and formal recycling network mini-

Table 4. Characteristics of waste from Indian cities classified with respect to their population (in millions)

Population Range (millions)	Number of cities under Observation	Waste Quantity (TPD)	Waste Generation Rate (kg/c/day)	Recyclable (%)	C/N Ratio	Moisture (%)	Compostable (%)	HCV (Kcal/Kg)
< 0.1	8	22.5 ± 23.1	0.4 ± 0.2	21.0 ± 4.9	26.2 ± 7.1	48.6 ± 12.7	51.7 ± 12.5	2161.0 ± 786.8
0.1 - 0.5	11	96.8 ± 65.2	0.4 ± 0.1	19.6 ± 6.6	26.4 ± 6.8	49.8 ± 11.9	51.2 ± 8.0	2162.3 ± 1079.9
0.5 - 1	16	328.1 ± 139.8	0.4 ± 0.2	16.2 ± 4.1	28.9 ± 10.7	47.7 ± 15.3	54.2 ± 9.0	1480.9 ± 560.2
1 - 2	11	480.8 ± 151.3	0.4 ± 0.1	17.2 ± 4.7	27.1 ± 11.4	40.7 ± 13.3	47.4 ± 4.7	1410.9 ± 711.9
2 - 3	6	859.7 ± 301.1	0.4 ± 0.1	13.8 ± 2.3	32.7 ± 9.0	47.0 ± 15.2	51.2 ± 6.8	1685.8 ± 754.9
3 - 10	5	2169.4 ± 705	0.5 ± 0.1	16.7 ± 5.2	30.3 ± 3.4	45.2 ± 8.3	47.8 ± 6.2	1866.0 ± 656.5
> 10	2	5621 ± 425.7	0.5 ± 0.1	16.1 ± 0.8	37.0 ± 2.9	51.5 ± 3.5	58.4 ± 5.7	1794.0 ± 11.3

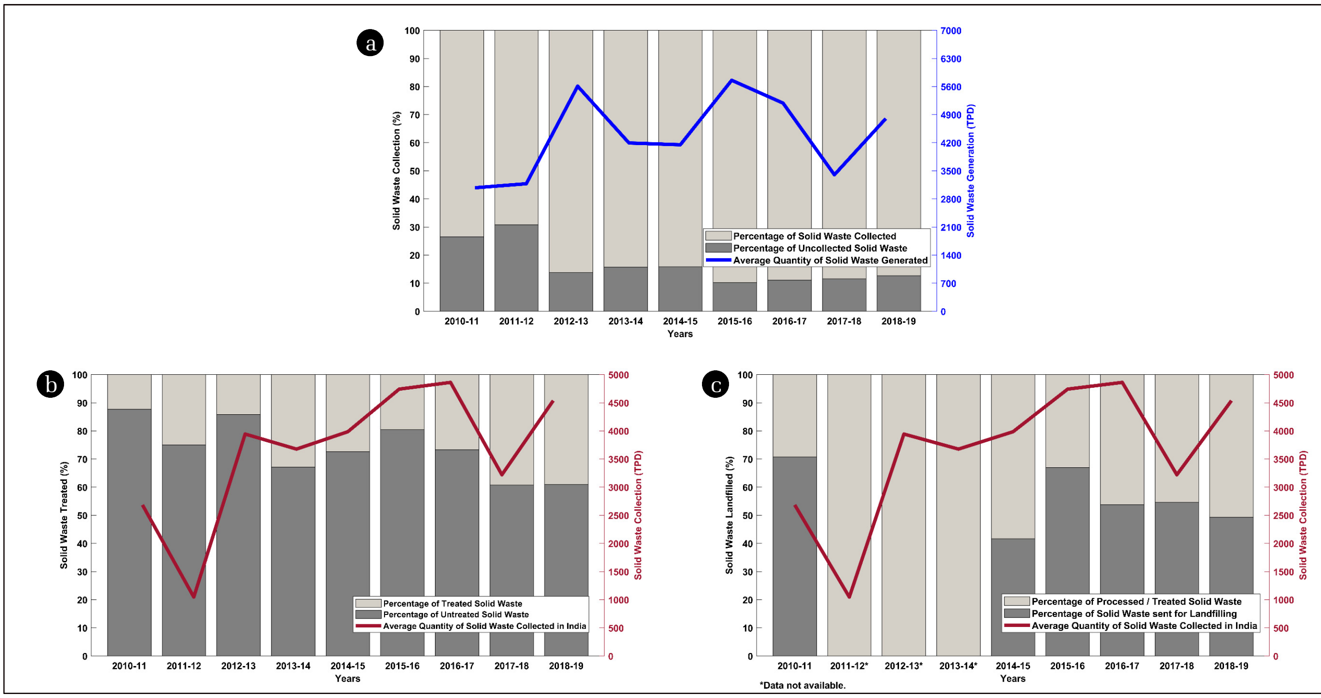

Fig. 4. Percentage of Solid waste collection, treatment, and disposal at landfills w.r.t Solid waste collected in India

mizes solid waste. The rag pickers collect metals, plastics, glass, leather, rubber, textiles, paper/cardboard, and other recyclables. Many households also sell recyclables to itinerant waste buyers. The recyclable materials pass from the rag pickers or itinerant buyers to small waste dealers. After that, it reaches middle-level dealers and finally reaches recycling units. End-users of cleaned and sorted recyclables are the recycling units or factories which use these recyclables as raw materials for manufacturing a new product. On average, about 50.72% of the waste collected in India is minimized, recycled, and reused. Hence, landfills are saved from being piled up with a large volume of garbage. Jharkhand, Uttar Pradesh, Goa, West Bengal, Andhra Pradesh / Telangana, and Chhattisgarh recycle more than 90% of the waste collected. Andaman & Nicobar Islands, Manipur, Tamil Nadu, Maharashtra, and Delhi recycle just over 50% of the waste. The lowest amounts of waste recycling are observed in Haryana, Gujarat, Daman & Diu, Meghalaya, Puducherry, and Odisha. Due to a lack of data, no observation could be made about states/UTs such as Arunachal Pradesh, Assam, Bihar, Jammu & Kashmir, Karnataka, Kerala, Lakshadweep, Mizoram, and Uttarakhand. Major waste-producing states shall coordinate and increase waste minimization, recycling, and reuse. A serious impetus is required to push the recycling sector of the blockages in India. Recycling is a dirty and unhygienic activity; waste is often littered around the recycling units. Although measuring the recycling sector's contribution to environmental conservation is difficult to ascertain, it plays an essential role in saving virgin materials.

3.4.2. Collection, storage, and segregation of waste

Despite the efforts to improve the waste collection mechanism, more than half of the cities still fail to collect even 25% of their solid waste. On average, 17% of all the waste generated in India remains uncollected. Cities such as Mumbai, Delhi, and Hyderabad collected more than 90% of their solid waste and put it into the conventional waste processing method. Maharashtra state can collect 99.3 % of its generated solid waste. Other states have not fared well in collecting their solid waste. Regardless of the trend of waste generation, the segregation of wastes is the bottleneck. In India, waste collection and segregation are carried out in the same instance. The onus lies with the citizen segregating and disposing of waste in the receptacles. However, some municipal agencies also provide door-to-door collection and transport of waste to disposal sites by mini-dumpers. They utilize covered garbage bins of 12 to 16 tons capacity and street dustbins in the societies. Management of open areas for the storage of solid waste requires further efforts. Metal containers with color codes to help MSW segregation (green containers for biodegradable waste and blue containers for non-biodegradable wastes) exist in most municipal areas. Municipal workers collect the waste from domestic and commercial spaces and bring it to the nearest waste receptacles. The cantonment boards also have garbage collection points in civilian and military areas. Street-sweeping in the military area is undertaken by the military, while sweeping in the civilian areas is conducted by the respective Cantonment Boards. A combined community bins and door-to-door collection system is necessary to avoid street littering [131].

3.4.3. Transport and transfer

Waste transportation is a significant part of municipal expenditure. Door-to-door collection vehicles equipped with two color-coded containers increase public awareness of segregation at the source. Municipal agencies across the country maintain a fleet of vehicles that collect MSW from waste receptacles and transport it to the disposal sites. The primary haulers are refuse removal trucks, tractor-trailers, mini dumpers, loaders in urban areas, and carts in rural areas. Methods of transportation of MSW depend on the type of collection points. The logistical system faces difficulty transporting solid waste and works at low efficiency. Besides, the uncovered truck is a nuisance in the city; they spread the garbage all along their way to landfill sites. The municipal agencies carry out the MSW collection, transportation, disposal, and treatment. Disposal trucks are adequately covered to prevent the spreading of the collected waste on the streets. About three-fourths of expenditure in solid waste management is consumed against the collection and transportation of waste. Approximately Rs. 800 per ton ($10.45/ton) is spent on waste transportation in India. Hence, much focus is required to optimize the activity. Waste disposal routes shall be designed to achieve logistical efficiency and cost optimization. The transportation and logistics system for waste management needs significant overhauling using modern tools. Logistical models based on GIS suggest it improved overall efficiency and optimization of resources [132-135]. States like Delhi, Mumbai, and Ahmedabad are moving forward with a decentralized approach to cutting transportation costs [27].

3.4.4. Treatment and disposal

Almost 90% of landfills in India, including Ghazipur and Bhalswa in Delhi, and Deonar in Mumbai, do not have landfill liners and lack leachate collection or re-circulation system [117,136]. The disposed of MSW is spread evenly and compressed by a single bulldozer movement and covered by soil and silt. Rag pickers also carry out their recycling operations at landfill sites. Animals like vultures, pigs, cows, and dogs are common on the sites [137]. A direct rational relation between the quantity of waste collected and waste sent to landfills is shown in Fig. 4. It also presents an inverse relationship between solid waste treated and solid waste generated. The more solid waste is collected, the more waste is sent to landfills. It points toward the inadequacy of treatment facilities in India. Only 26% of the collected solid waste undergoes treatment. Lack of segregation primarily causes processing plants for palletization and composting to work without adequate bio-degradable waste. Modern, eco-friendly treatment technologies need more emphasis than incineration [138]. As a method of waste disposal, landfilling needs substantial efforts to prevent its threats. An under-drainage system shall be available to provide efficient and adequate cover for the successive landfill layer with ventilation. Moreover, regular monitoring programs check greenhouse gas emissions into the air and leachate into the water environment. Greening and covering the landfill limits the wastes from birds and scavengers and prevent bio-magnification [108].

4. Key Challenges and Solutions to Solid Waste Management in India

Municipal facilities are improving, yet the most significant challenge for effective municipal SWM in India lies with the weak organizational structure; unscientific methods, financial constraints; shortage of low-lying land for landfilling, and, most importantly, lack of public awareness [115,118,124,127,139]. In India, solid waste management faces severe problems as only a fraction of the waste is disposed of appropriately. With numerous efforts, municipal agencies across India have increased waste collection coverage. However, about 18% of the waste remains uncollected. A meagre amount of waste is processed and treated for recycling or energy recovery. Several landfill sites, including larger ones such as Ghazipur, Bhalswa, Okhla in Delhi, and Deonar in Mumbai, have already reached their design life and are overflowing. Developing and operating new landfill sites using the scientific disposal method is challenging. Citizens should be aware of segregating waste at the source, avoiding littering on roadsides, and observing their duties towards the environment [25,131]. The informal sector, including the rag-pickers, manages to recycle in the cities. It is essential to segregate recyclable solid waste components from garbage bins and landfills [131]. Authorities have implemented policy measures to include the unorganized sector in solid waste management. It has increased waste collection and segregation and simultaneously solves logistical problems.

4.1. Waste-to-Energy Conversion

The solid, liquid, and gaseous discharges from industrial processes possess different WTE potential. Urban waste (solid and liquid discharges), cattle farm (solid discharges), distillery (liquid discharges), vegetable raw (solid discharges), poultry (solid discharges), slaughterhouse (liquid discharges), paper (liquid discharges), fruit raw (solid discharges), sugar press mud (solid discharges) are the top sectors in India with more than 5225 MW of WTE potential [140]. Until 2020, biogas generation projects have been set up in Uttar Pradesh, Madhya Pradesh, Andhra Pradesh, and Telangana, generating a cumulative installed capacity of 37900 m^3/day. States such as Maharashtra, Karnataka, and Punjab have established 4 MW power projects based on WTE. Bio-CNG generation has increased with 25731 kg/day cumulative installed capacity. Moreover, 139.80 MW grid-interactive and 114.93 MW off-grid power projects are operational. Presently, 57426 m^3 of biogas is generated per day from industrial units in Madhya Pradesh and Maharashtra from maize and starch processing. Ahmedabad and Surat generate 8600 kg/day of Bio-CNG from vegetable waste, hotel waste, cow dung, and sewage treatment plants. Wastes from gardens, poultry, animal husbandry, slaughterhouses, distillery, sugar manufacture, dairy, oil refining, leather processing, food, and food grain processing shall be employed aggressively for WTE. Self-sufficient industries shall be encouraged with in-house power generation from their wastes using WTE and other renewable energy sources.

4.2. Greenhouse Gas Emission

India is a developing nation improving its technology and infrastructure for waste-to-energy generation. Energy potential here can increase by tapping gases such as methane emitted from landfills. It can quickly and effectively be used as biogas for heat and electricity generation. On the contrary, landfills are the major contributor to methane emissions [98,117,137,141,142]. Landfill gas remains untapped as a potential source of energy. IPCC states that 30% of the total GHG emission to the environment is from landfills. Delhi contributes to 10% of the total methane emission from MSW [4,34,143]. Further efforts are required to improve sustainability and reduce GHG emissions [124]. IPCC reports the worsening of climate change issues [144].

4.3. Health Issues

The landfills' wastes are mainly polymers, plastics, chemicals, electronic components, biomedical products, construction and demolition waste, household wastes, and many substances. Contaminants such as organic acids and heavy metals are proven allergens, potential carcinogens, and toxic, causing acute and chronic ailments. Cancer, congenital disabilities, tumor formation, reproductive defects, kidney problems, and cardiac, renal, and circulatory issues are known diseases handling solid wastes. There exists evidential proof that operators and manual workers suffer from acute toxicity to the kidney and nervous system [114]. Chronic diseases, such as cadmium poisoning and mercury poisoning, affect the population engaged in solid waste management. Moreover, the health risk is not limited to the landfill but extends to several kilometers from the landfill. Municipal workers and other communities associated with the handling of solid waste and management face respiratory and cardiovascular health issues such as bacterial infection, impaired lung function, low haemoglobin / RBC, altered immunity, allergy, asthma, and inflammation in the nose, throat, lung, and other impairments bear their mark [145].

4.4. Solutions to Key challenges

Awareness is an issue that mars the public and administration's potential. Both need to keep abreast of the present scenario and the fate of SWM. Awareness-related matters can be addressed by assessing public awareness and involvement through knowledge gap analysis, which promotes informed decision-making. Hence, better policy formulation, clear laws, and fee methodology. Improved public awareness plays a pivotal role in deciding the fate of the environment during pilgrimage and religious events. A moral and ethical value system toward solid waste management enhances the quality and quantity of waste collected. Numerous studies have pointed out that a door-to-door collection system is better at segregation than a point collection system. Improvement in segregation primarily impacts waste conversion into recycled goods and energy resources. This helps to obviate the emission of greenhouse gasses. Awareness of the administrative system can be increased by learning from advanced countries. Techniques such as artificial intelligence, machine learning, convolutional neural networks, internet-of-things, computer vision, etc., followed in developed countries, may help the automated identification and segregation of waste.

Waste-to-energy issues can be resolved by exploring newer avenues where untapped resources, such as the provisioning of landfill gas as fuel on a large scale—innovative ways to convert raw wastes into high-energy producing substances. Improved efficiency of collection and segregation is possible by forming a workable collection plan, and optimized route map created using geo-positional attributes. It will invariably reduce time-operation and savings in labor, distance, and pathways. Multi-criteria decision support systems can be used to select an appropriate methodology for waste treatment and save resources. Focus on environment-friendly ways such as composting shall be encouraged.

GHG emissions can be reduced by enabling a circular economy-based framework for industrialized products. The indirect causes shall also be identified and addressed in addition to factors directly affecting GHG emissions. An integrated solid waste management approach is a strategic approach to sustainable management of solid wastes covering all sources and all aspects, covering generation, segregation, transfer, sorting, treatment, recovery, and disposal in an integrated manner, with an emphasis on maximizing resource use efficiency, shall be implemented. Compared to incineration and landfilling, simple and natural methods such as composting are the best at reducing GHG emissions. Employing strategically placed storage areas of waste to facilitate quick loading and disposal also affects the emission of GHGs. Another avenue to reduce the generation of GHG is recycling. Solid waste, whenever possible, shall be reused and recycled. Recycling of construction and demolition minimizes the requirement for virgin materials to a great extent. India possesses a high potential for developing a culture of recycling in day-to-day life. GIS-based optimized routing plan for the transport and transit of wastes proves to have considerable savings in CO2 emission.

Numerous health issues from handling, processing and exposure to solid wastes are avoidable. Measures such as minimizing waste generation by studying and applying life-cycle analysis within the manufacturing process. A product designed for the smallest waste footprint can significantly influence waste generation. Disposal of waste may be kept in check for emission of heavy metals and other toxic chemicals. At present, open burning and dumping are the most prevalent methods of waste disposal Advancement in disposal technology is warranted for environment-friendly disposal methods. Reduction of Impact through an early warning system and decision-making system based on continuous analysis of temporal and spatial variation of waste characteristics is required. Mitigation shall not only focus on immediate impact minimization but also work on a long-term solution for environmental health. Due to the recent COVID-19 pandemic, a dedicated healthcare waste handling system, including measures for recycling, treatment, and disposal, has been established in many countries.

5. Conclusion

The study concludes that prompt action is necessary for data management, training, education, planning, monitoring, strict policy changes with strong legislation, the establishment of a reliable regulatory system, proper and effective management of all waste streams, public awareness, and best housekeeping practices for adequate implementation of solid waste management in the developing countries. This state-of-the-art review examines the literature on management, framework, awareness, generation, collection, segregation, characterization, minimization, storage, transport, treatment, recycling, disposal, impact, GHG emission, COVID-19, and waste-to-energy aspects of solid waste management. It finds that one of the significant challenges to SWM is the steps to be employed to reverse the impacts caused by the previously used disposal methods. Despite plenty of studies on solid waste management aspects such as exploring and implementing scientific monitoring, treatment, and disposal methods; overhauling the organizational structure; searching for best practices for recycling and recovery from solid waste; tapping the waste-to-energy potential to its fullest extent from landfill-gas-to-energy and waste-to-energy; search for low-cost, and location-based strategies to achieve zero waste disposal at all sources of waste; achieving a superior level of awareness among citizens needs to be the emphasis. Future research in the solid waste management sector shall also focus on the lack of solid waste management infrastructure for rapidly growing urban areas, energy conversion from wastes and tapping landfill gasses, and trapping greenhouse gas emissions from various solid waste processing and disposal. After rigorous review, this paper concludes that all the World's developing and underdeveloped countries face similar solid waste management problems. Therefore, all countries' cumulative efforts for managing solid waste can bring forth excellent results around the globe.

Conflict-of-Interest

The authors declare that they have no conflict of interest.

Author Contributions

A.A.G. (Assistant Professor) conducted the literature review and data analysis and wrote the manuscript. S.K.S. (Professor) revised the manuscript.

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