Environmental Technology & Innovation 29 (2023) 103017

Contents lists available at ScienceDirect

Environmental Technology & Innovation

journal homepage: www.elsevier.com/locate/eti

A comprehensive insight into Waste to Energy conversion strategies in India and its associated air pollution hazard

Arijeet Karmakar [a], Trisha Daftari [b], Sivagami K. [b], Mohammed Rehaan Chandan [b], Aabid Hussain Shaik [b], Bandaru Kiran [b], Samarshi Chakraborty [b,*]

[a] *School of Mechanical Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, India*
[b] *Colloids and Polymer Research Group, School of Chemical Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, India*

ARTICLE INFO

Article history:
Received 16 August 2022
Received in revised form 9 December 2022
Accepted 9 January 2023
Available online 13 January 2023

Keywords:
Waste to Energy
Municipal solid waste
Air pollution control
Health hazards
Toxicological effect
Environmental impact assessment

ABSTRACT

With the increasing demand for cheap energy sources, Waste-to-Energy (WtE) strategies are gaining importance across the world. In India, such strategies have a two-way benefit i.e., generating electricity using municipal solid waste and helping in solid waste management by reducing the need for landfill sites. In this review, the focus has been given to identifying and analysing toxicological problems related to major air pollutants emitted during the WtE conversion process. Depending upon the country and state, the nature of solid waste and emission standards vary which directly impacts air quality standards and steps required to reduce such emissions. In India, the percentage of wet solid waste is much higher than dry solid waste which significantly deters the economic and technical feasibility of WtE plants. The heating value of solid waste reduces significantly when improper waste segregation occurs which is detrimental from both the electricity generation and pollution viewpoint. These problems associated with solid waste management have been covered in detail in the manuscript. This review article also provides a comparative study of Indian WtE plants with their global specifically European counterparts. The adverse effect of pollutants emitted from WtE plants on human health has been discussed in the article along with the air pollution control methods to mitigate the problem. To gauge the importance and limitation of WtE plants over conventional solid waste management strategies such as landfills, the environmental impact assessment has also been discussed which further justifies the necessity of the present article.

Contents

1. Introduction 2
2. Introduction to waste-to-energy generation 3
    2.1. Thermochemical waste-to-energy processes 4
    2.2. Biochemical waste-to-energy processes 4
3. Potential and limitations of waste-to-energy plants in India 5
    3.1. Municipal solid waste (MSW) generation 6
    3.2. Current installed capacities of waste-to-energy plants in India 6
    3.3. Challenges to waste-to-energy projects in India 7

---

* Correspondence to: School of Chemical Engineering, Vellore Institute of Technology, Vellore, India.
E-mail address: samarshi.chakraborty@vit.ac.in (S. Chakraborty).

https://doi.org/10.1016/j.eti.2023.103017

3.3.1. Improper management of municipal solid waste and associated social stigma 7
3.3.2. Lack of proper financial investment and political issues 8
3.3.3. Lack of regulations and implementations of policies 8
3.3.4. Conflict of public interests 9
3.3.5. Lack of indigenous technological advancements 9
4. Comparative analysis of global WtE standards with the Indian scenario 9
5. Identification of major air pollutants produced during WtE processes and the strategies for their removal from the flue gas stream 10
6. Health hazards caused by exposure to emissions from WtE plants 10
7. Environmental impact assessment of various WtE plants over landfill 12
8. Selection of best strategy for WtE conversion 15
9. Need for strict government regulation and monitoring 15
10. Conclusion 16
CRediT authorship contribution statement 17
Declaration of competing interest 17
Data availability 17
Appendix A. Supplementary data 17
References 18

---

1. Introduction

In this era of sustainable growth, trends are moving away from conventional (non-renewable) resources towards renewable resources to satisfy the energy requirement of the general population without creating negative environmental impacts. A worldwide effort is being made to recognize the potential of every nation in the solid waste management sector and its subsequent utilization in the energy recovery sector. Developed countries like the US have recognized energy recovery potential from waste as a sustainable source of energy (Cheng and Hu, 2010). Waste to energy (WtE) is already being used by developed countries as a means of tackling several waste-related environmental problems (Brunner and Rechberger, 2015). It has already come to notice that several countries and cities are running out of land for dumping municipal solid waste. As a result, cities such as New York, London, Montreal, Toronto, etc. have to move thousands of tons of waste every day from the city area to a landfill site located far away and unprocessed waste to low-income countries. In countries like China, more than 66% of the cities have already filled their landfill sites beyond their capacities (Curry and Pillay, 2012). WtE conversion using municipal solid wastes (MSW) is gaining importance due to the following reasons; (a) shortage of lands that can be utilized as landfills and the rate at which WtE techniques decrease the volume of waste, (b) it helps to minimize the impact on the environment, and (c) it can be used for generating both electricity and heat as well as providing a financial incentive by recovery of valuable components like metals, plastics, and other recyclable solid wastes which can be segregated (Lombardi et al., 2012). However, even with the best segregation systems, many recyclable materials are still present in segregated solid waste used as WtE feedstock (Cimpan and Wenzel, 2013). Among the many waste-to-energy technologies available, the oldest and most widely used WtE method is incineration. However, suitable technologies differ from country to country due to various local factors like energy requirements, culture, climate, economic development, etc. One such important factor is the nature and composition of MSW. It has been observed that developing countries like India have higher moisture and organic contents while the European and North American nations mostly have inorganic materials in their MSW (Moya et al., 2017). This means that the most commonly used WtE technology i.e., incineration, is a less favourable option in India. European Union (EU) has made significant advances in the field of WtE and they targeted to achieve the following targets by 2020: (a) utilize 20% renewable energy, and (b) decrease the CO_2 emissions by 20% (Münster and Meibom, 2011). Currently, the EU uses 22% renewable energy and also achieved its CO_2 emission reduction targets. EU plans to achieve a minimum of 32% renewable energy utilization and a 55% reduction in greenhouse gas (GHG) emission target by 2030 (Commission and Energy, 2022). EU achieved its 2020 pre-set targets even while following a prioritized waste treatment or management policy. Priorities are given in the order of highest to lowest as follows: (a) prevent, (b) reuse, (c) recycle, (d) recover, and (e) landfill (Dong et al., 2018).

There are several challenges and barriers that India has to overcome while dealing with WtE technologies. Some of the major concerns include uncertain policies, socio-economic and financial challenges, profitability, and sustainability as compared to non-renewable resources (Yap and Nixon, 2015). Another major concern and cause for resentment among the general population for WtE technologies are related to their toxic pollutant emissions like dioxins/furans, polycyclic aromatic hydrocarbons (PAHs), etc. These hazardous pollutants become a part of the flue gases coming out of WtE plants as well as the solid residue which is dumped at the landfill sites. Even though WtE technologies play a role in minimizing the effect of GHG emissions as compared to landfills, still a large number of greenhouse gases (GHG), volatile organic components (VOC), and persistent organic pollutants (POP) are emitted from these facilities (Lam et al., 2010). Hence, WtE facilities are not a means to prevent but just a medium to delay the inevitable. There are some important criteria to be met while constructing a WtE plant: (a) proper measures have to be taken to eliminate or reduce the hazardous emissions and waste residues so that their impacts on public health and the environment can be controlled, (b) WtE plant

List of abbreviations

AD	Anaerobic digestion
APC	Air Pollution Control
CFB	Circulating Fluidized Bed
CPCB	Central Pollution Control Board
EIA	Environmental Impact Assessment
EPA	Environment Protection Agency
EU	European Union
GHG	Green House Gases
GW	Gigawatt
GWP	Global Warming Potential
MBT	Mechanical–Biological Treatment
MNRE	Ministry of New and Renewable Energy
MoEF	Ministry of Environment and Forests
MSW	Municipal Solid Waste
MSWI	Municipal Solid Waste Incineration
MW	Megawatt
NR	Not Reported
PAHs	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
POP	Persistent Organic Pollutants
POCP	Photochemical Ozone Creation Potential
RDF	Refuse Derived Fuel
TCDD	2,3,7,8-TetraChloroDibenzoDioxin
TOC	Total Organic Carbon
TPD	Tonnes Per Day
ULB	Urban Local Bodies
UT	Union Territory
VAP	Value-Added Products
VOCs	Volatile Organic Compounds
WtE	Waste to Energy

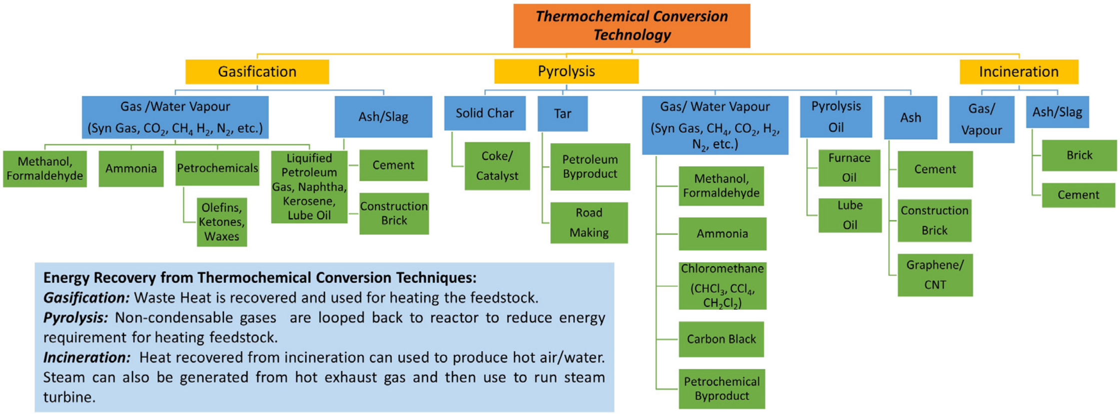
operation and maintenance should be working on a sustainable cycle, and (c) there should be a net positive outcome from the WtE plants, taking into consideration all the emissions and impact indicators (Skaggs et al., 2018).

Currently, India has only been able to utilize less than 5% of its total potential in the WtE sector (Chinwan and Pant, 2014, MNRE Report 2021). Compared to the quantity of waste produced, the number of working incineration plants in India is very low. Very few studies have compared Indian and European WtE scenarios. Such studies would help in the further realization of areas in which India still lacks significantly. There is also an insufficient number of case studies that measure and evaluate the emissions from WtE plants in India. In the absence of stringent air pollution laws in India, unlike in other developed countries, it is impossible to draw quality conclusions in the fields of environmental impact assessment of WtE plants in India. A developing country like India faces many social, cultural, and political issues. There is a genuine lack of strategies that take into consideration these factors specific to Indian scenarios which again leads to a deficiency of sufficient reliable data to draw proper conclusions for policymaking.

In this light, this paper aims to answer some unanswered questions which can be helpful in the future development of suitable WtE technologies in India. The objectives of this paper are (a) a quantitative review of India's WtE potential and installed capacity in different states and comparison with the WtE sector of European and other developed countries, (b) an identification of major emissions and air pollutants from WtE facilities, and (c) a qualitative review of the health hazards for people living in the vicinity of such facilities, (d) an identification of factors which play a major role in restricting India's pace for WtE development, (e) a qualitative study of environmental impacts of various existing WtE technologies and their comparison with the environmental impact of landfills, and (f) a role and effect of stringent governmental policies in reshaping India's WtE scenario.

2. Introduction to waste-to-energy generation

Converting waste into energy is not a revolutionary idea, but it is a renewable energy method that requires significant attention. Various energy conversion technologies are available in the literature to produce energy from solid waste.



Energy Recovery from Thermochemical Conversion Techniques:
Gasification: Waste Heat is recovered and used for heating the feedstock.
Pyrolysis: Non-condensable gases are looped back to reactor to reduce energy requirement for heating feedstock.
Incineration: Heat recovered from incineration can used to produce hot air/water. Steam can also be generated from hot exhaust gas and then use to run steam turbine.

Fig. 1. Different thermochemical conversion processes for WtE and their products.

Despite different strategies, the selection of a suitable technique for energy conversion is a challenging task that depends on the numerous physicochemical properties of the waste, the quantity of waste feedstock, and the desired form of energy (Hamad et al., 2014). The traditional method of energy production for heating or electricity generation also finds difficulty in replacing other energy sources with renewable energy resources in the energy market due to negative environmental impacts. WtE offers a cost-effective approach to solving the problems of energy demand and municipal solid waste (MSW) management. These approaches mainly involve three key pathways- thermochemical, physicochemical, and biochemical processes (Ouda et al., 2016). Among these approaches, electricity, and heat can be produced by thermal technologies, whereas biogas can be generated by a biochemical process (anaerobic digestion) which can be further used either for electricity and heat production or as a transport fuel (Fruergaard and Astrup, 2011). Although extensive research has been conducted in India and abroad on waste-to-energy conversion, a concise summary of works related to its commercialization has been reported in this section. The following technologies like incineration, gasification, pyrolysis, anaerobic digestion, and ethanol fermentation are mainly used for large-scale applications.

2.1. Thermochemical waste-to-energy processes

Thermochemical technologies are generally used to convert waste into heat, electricity, and other value-added products (VAP) by subjecting waste to high temperatures (Ouda et al., 2016). Thermal conversion is considered a part of integrated waste management technology (Eddine and Salah, 2012; Hamad et al., 2014). The major thermochemical conversion methods are (a) incineration, (b) gasification, and (c) pyrolysis. All these methods are recommended and suitable for waste having a moisture content of less than 20% (Sadiq and Kaneesamkandi, 2013). Although different methods are available, the most traditional way of converting Waste-to-Energy directly involves producing heat through direct combustion or incineration. Each conversion technology offers a different product selection, altered input specifications, and employs dissimilar configurations of equipment to recover the chemical value of the waste, rather than its energy value (Bosmans et al., 2013). Moreover, various by-products are produced from these processes and these by-products can be further utilized as raw materials for the production of other various petrochemical products like olefin, carbon black, alcohol, etc. However, the major advantage of thermal processes lies in keeping most of the hazardous bacteria and pathogens sterile. The advantages and disadvantages are discussed in detail in Table 1. Currently, the thermochemical process is the most preferred WtE technology in the majority of European countries Fig. 1 depicts different thermochemical conversion processes and their associated products (Ionescu et al., 2013). Energy recovery from various thermal WtE is also depicted in Fig. 1.

2.2. Biochemical waste-to-energy processes

Conversion of waste to energy through the biochemical process involves the usage of bacterial and other microorganism enzymes to break down biomass. Biochemical conversion is one of the few methods that offer an environmental-friendly approach for MSW to acquire energy and fuel (Beyene et al., 2018). Biochemical processes such as anaerobic digestion and fermentation produce renewable energy and several by-products. This method is considered a reliable technology for the treatment of wet, organic waste. A large portion of the Indian MSW consists of digestible and biodegradable matter such as market vegetable wastes, kitchen wastes, papers, wood, etc. It is more suitable to use biochemical processes where segregation is possible and the initial capital is less. Biogas with a pure methane content greater than 95% can be generated by the current advanced digester systems viz. passive systems, low-rate systems, and high-rate digester systems (Sadiq and Kaneesamkandi, 2013). Table 1 summarizes different key parameters (operating temperature, pressure, operating procedure, type of waste used, applications, advantages & disadvantages, etc.) of thermal and biochemical WtE processes.

Table 1
Comparison of different thermochemical WtE processes - Incineration, gasification, and pyrolysis and biochemical WtE processes - Anaerobic digestion and ethanol fermentation.

Key parameters	Thermochemical WtE process			Biochemical WtE process	
	Incineration	Gasification	Pyrolysis	Anaerobic digestion	Ethanol fermentation
Operating temperature (°C)	750–1100 °C (Beyene et al., 2018)	800–1200 °C (Beyene et al., 2018)	300–1300 °C (Beyene et al., 2018)	Mesophilic range- 30–38 °C Thermophilic range- 44–57 °C (Hilkiah Igoni et al., 2008)	30–38 °C in the first stage 55–70 °C in the next stage (Hettenhaus, 1998)
Operating pressure (bar)	1.013 bar (World and Washington, 1999) (Vary depending on raw material composition and product requirement)	1.013-62 bar (Phillips, 2006) (Vary depending on raw material composition and product requirement)	1.013 bar (Zaman et al., 2017) (Vary depending on raw material composition and product requirement)	1.033 bar (Chen et al., 2014) (Vary depending on raw material composition and product requirement)	1.013 bar (Galanakis et al., 2012)
Operation environment	In presence of air and oxygen	Gasification agents like O_2 and H_2O are present	An inert gas environment such as nitrogen is present and oxidizing agents are absent	Organic matter from the MSW is converted into useful substances in the absence of oxygen (Beyene et al., 2018).	Organic matter is fermented in the presence of yeast which is used as an enzyme (Beyene et al., 2018).
Energy recovery efficiency	25–30% (Ouda et al., 2016)	17% (Ouda et al., 2016)	80% (Ouda et al., 2016)	25% (Nizami et al., 2015)	–
Main objective	Large-scale production of high-temperature flue gases from waste.	Achieving a higher calorific value of gases instead of volume	Obtaining large quantities of coke, gases, and condensed phases (Pandey et al., 2016).	Production of Acetic acid and carbon dioxide by fermentation and methane and acetic acid by methanogenesis (Ouda et al., 2016).	Hydrolysis of sucrose to produce Ethanol (main product) and CO_2 (by-product) (Gumisiriza et al., 2017; Lin and Tanaka, 2006).
Type of waste	Mostly suitable for medical waste, hazardous waste, and MSW.	Wastes contain large amounts of organic and recyclable matter (Beyene et al., 2018).	Biodegradable wastes such as cloth, paper, food wastes, etc., and plastic waste as well.	Useful for organic matter such as animal manure, wastewater bio soils, and food waste (Beyene et al., 2018).	Mostly include food waste such as corn, potato, etc. (Kalogo et al., 2007)
Methods used	Three types- fluidized bed, rotatory kiln, and gate incinerator (Helsen and Bosmans, 2010).	Three types: fixed bed, fluidized bed, and entrained flow gasifier (Bosmans et al., 2013).	Three types: conventional/slow pyrolysis, fast pyrolysis, and ultra-fast/flash pyrolysis (Beyene et al., 2018).	The number of stages, temperature, rate of conversion of organic matter, and water availability determine the type of digester (Nizami et al., 2015).	Sugar is directly fermented into ethanol whereas starch and cellulose are first converted into sugar by treatment with different enzymes and mineral acids respectively (Beyene et al., 2018).
Operating procedure	Feed after preparation from stored waste is oxidized in the combustion chamber where ash is handled and heat is recovered.	Organic components after pre-treatment undergo gasification to obtain synthesized gas containing CH_4, CO, CO_2, H_2, steam, etc. (Kumar, 2000).	The slurry is dried after size reduction to enhance reaction efficiency, followed by pyrolysis to obtain solid and metal residues (Bosmans et al., 2013; Helsen and Bosmans, 2010).	Two types are - wet and dry milling. Larger and more complex organic substances are broken down into soluble organic substances by hydrolysis.	Post segregation, recycling, treatment, and fine shredding, the waste undergoes simultaneous hydrolysis and fermentation (to increase yield).
Applications	Waste materials are subjected to complete oxidation to obtain energy as heat which is used for electricity generation (Cucchiella et al., 2014).	Produces synthesis gas through partial oxidation which is used as raw material in the industry and for electricity generation (Bosmans et al., 2013).	Secondary treatment of pyrolysis gas and pyrolysis coke is done to extract oil mixtures that are as useful as fuels (Bosmans et al., 2013).	Biogas produced is used for energy generation and along with the slurry can be used as a fertilizer (Zaman, 2013).	Ethanol is used as a fuel for electricity generation, can be blended with gasoline as an alternative fuel, and is a raw material in various chemical industries (Lin and Tanaka, 2006).
Advantages	• The weight of waste reduces to one-fourth and the volume to up to one-tenth compared to the original (Ouda et al., 2016). • Owing to their noiseless operation and low space requirements, plants can be constructed inside city boundaries.	• Reduces the volume, weight, and ash residue of waste greatly and produces lesser and non-hazardous air and solid pollutants (Ouda et al., 2016). • Plants require smaller air pollution control systems as the emissions are less. This reduces the cost of plants significantly (Bosmans et al., 2013).	• Products can be easily separated. It also stops the transfer of harmful additives into new products as part of the recycling chain (Helsen and Bosmans, 2010). • The power generation capacity of pyrolysis plants is high and the products obtained are high in calorific values (Nizami et al., 2015).	• Has the least social resistance and remains profitable even on a small scale. Useful for waste with high moisture content (Beyene et al., 2018). • The C/N ratio is maintained as food waste can be co-digested with raw sewage sludge which provides enough nutrients.	• Highly suitable for special waste collected directly from farms, wood mills, or any waste which has a high content of organic matter. • Final products have negligible chances of contamination by microflora (Beyene et al., 2018; Lin and Tanaka, 2006). This process leaves very less carbon footprints due to fewer GHG emissions (Malav et al., 2020).
Limitations	• Large quantities of air and water pollutants are liberated (carcinogenic pollutants like arsenic, mercury, lead, cadmium, dioxins, and furans) • Fouling and slagging in the plant and emission and ash treatment causes a 40%–70% increase in the working cost. more to its working cost (Ouda et al., 2016).	• Continuous cleaning and maintenance are required or else the by-products can cause damage to the whole system (Bosmans et al., 2013). This increases the cost of operation by a significant level (Ouda et al., 2016). • Designed for very specific input and output conditions and hence are not versatile. Improper handling of by-products (like tar), can be poisonous to the soil and environment (Kumar, 2000).	• Corrosion of tubes is a major issue. Additionally, the products obtained in the process are highly viscous and hence are more difficult to transport through pipes (Beyene et al., 2018; Kalyani and Pandey, 2014). • A compulsory pre-treatment of the MSW has to be carried out and the processing conditions have to be changed according to the type of waste composition (Bosmans et al., 2013).	• Requires an adequate supply of water, cattle dung, and substrates, and is a time-consuming process as inorganic materials have to be removed to enhance efficiency (Beyene et al., 2018; Kalyani and Pandey, 2014). • It cannot handle overloading and sudden charging of wastes. The build-up of volatile fatty acids and severe acidification affect the system permanently.	• The process is tedious and time-consuming as segregation is difficult (Lin and Tanaka, 2006). It has low sustainability in terms of cost of production and operation (Beyene et al., 2018). • The optimum temperature for hydrolysis is between 45–50 °C whereas the optimum temperature of the fermentation process is between 28–35 °C (Lin and Tanaka, 2006).
Latest technological advancements	MSWI (Municipal Solid Waste Incineration) Bottom Ash Technique (Joseph et al., 2018), Hydrothermal Carbonization (Pawlak-Kruczek et al., 2020)	Fluidized Bed Technology for gasification (Martinez et al., 2014)	Low cost catalyst (clay) based plastic pyrolysis (Fadillah et al., 2021)	Microbial Electrochemical technologies (Nikolausz and Kretzschmar, 2020)	Vacuum Recovery Technology (Huang et al., 2015).

In addition to the above Torrefaction, Plasma treatment also gains popularity among WtE valorization technologies (Gumisiriza et al., 2017).

3. Potential and limitations of waste-to-energy plants in India

There is huge potential for India in the market of waste to energy. However, due to various socio-economic and political issues, India has not been able to tap into using its potential to the fullest. Hence, this section shall explain the reasons why India has such huge potential, the current installed capacities of such WtE plants in India, and the challenges faced by India.

Table 2
Physical and chemical properties of Indian MSW (Rao et al., 2010; Singh et al., 2011).

Population range (Millions)	No of cities surveyed	Physical properties						
		Compostable (%)	Inert (%)	Metal (%)	Paper (%)		Rubber, leather, and synthetics (%)	Glass (%)
0.1–0.5	12	44.57	43.59	0.33	2.91		0.78	0.56
0.5–1.0	15	40.04	48.38	0.32	2.95		0.73	0.56
1.0–2.0	9	38.95	44.73	0.49	4.71		0.71	0.46
2.0–5.0	3	56.57	40.07	0.59	3.18		0.48	0.48
5.0 and above	4	30.84	53.9	0.8	6.43		0.28	0.94
Chemical properties								
Population range (Millions)	No of cities surveyed	Nitrogen as total nitrogen (%)	Phosphorous as P_2O_5 (%)	Potassium as K_2O (%)	Organic matter (%)	C/N ratio	Moisture content (%)	Calorific value (kcal/kg)
0.1–0.5	12	0.71	0.63	0.83	37.09	30.94	25.81	1009.89
0.5–1.0	15	0.66	0.56	0.69	25.14	21.13	19.52	900.61
1.0–2.0	9	0.64	0.82	0.72	26.89	23.68	26.98	980.05
2.0–5.0	3	0.56	0.69	0.78	25.60	22.45	21.03	907.18
5.0 and above	4	0.56	0.52	0.52	39.07	30.11	38.72	800.70

*Population-wise data.

3.1. Municipal solid waste (MSW) generation

Indian sources of solid municipal waste can broadly be classified into four types- residential, commercial, institutional, and municipal. These solid wastes are generated in residential areas, stores, hotels, restaurants, office buildings, market areas, schools, hospitals, parks, beaches, and recreational areas. The major components of Indian solid municipal waste are food wastes, plastics, textiles, synthetic materials, glasses, cardboard, paper, household wastes, metals, electronics, general wastes from recreational areas, and other hazardous wastes (Ranjith Kharvel Annepu Advisor and Themelis Stanley-Thompson Professor Emeritus, 2012).

As per the latest Central Pollution Control Board (CPCB) annual report (2020–21), the per capita solid waste generation in India is 119.07 gm/day. The MSW generated including all the states and union territories is around 160 038.90 TPD for the year 2020–21 as per the CPCB report. A task force was established for the implementation of the waste-to-energy projects in 2014 under the planning commission. According to their report, considering a 5% annual increment in waste generation, urban India is expected to generate 4,50,132 TPD and 1 195 000 TPD of waste, by 2031 and 2050, respectively (Report of the Task Force on Waste to Energy (Volume I) (In the context of Integrated MSW Management) Planning Commission, 2014). The major physical and chemical properties of the Indian MSW can be seen in Table 2. Among different types of MSW, compostable and biodegradable waste account for a major share. The rest consists of recyclables and inert materials. It was surveyed that in most cities having over 1 million population, more than 0.33% metals and more than 2.95% paper-based waste on a weight basis were found. Other components including glass, rubber, leather, and synthetics usually made a little more than 1% of the overall waste as per dry weight basis. Organic matter content, moisture content, nitrogen content, P_2O_5, K_2O, C/N ratio, moisture content, and calorific value of municipal solid wastes from different Indian cities have also been reported in Table 2. All these values vary with the population of the city. In the MSW collected, organic matter ranges from 25%–40%, moisture content ranges from 19%–39%, and total nitrogen content ranges between 0.56–0.71% (Malav et al., 2020; Kalyani and Pandey, 2014; Nandan et al., 2017; Ranjith Kharvel Annepu Advisor and Themelis Stanley-Thompson Professor Emeritus, 2012). Table 3 shows the energy content of various components of MSW suitable for energy generation (Abdallah et al., 2018; Akinshilo et al., 2019; Nizami et al., 2015). From the total municipal solid wastes generated in India alone, it can be estimated that around 3653 MW (See Table 5 and Supplementary Table 2) of electricity can be generated. However, the actual amount of energy generated is only around 4.6% of the potential figure (Annual Report 2020-21 on Implementation of Solid Waste Management Rules, 2016) (see Table 4).

3.2. Current installed capacities of waste-to-energy plants in India

The total installed capacity of WtE plants in India stands at 168.64 MW. Northern (63.95 MW) and southern (76.36 MW) India has the major share of installed and operational WtE facilities (MNRE, India Statistics, 2020-21) whereas eastern India does not have any operational WtE plant. In addition to existing operational plants, several new WtE plants are proposed, and under development, which will further add 102.1 MW capacity to existing power generation capacity in different states spread across India i.e. Haryana, Madhya Pradesh, Telangana, and Uttarakhand (Annual Report 2020-21 on Implementation of Solid Waste Management Rules, 2016). The current installed MSW-based electricity generation capacity only accounts for 4.6% of the overall potential which is 3653 MW (MNRE, India Statistics, 2020-21). It is to be mentioned that the total installed capacity of waste-to-energy plants has almost quadrupled in the past 15 years increasing from 43.5 MW in 2007 to 168.64 MW in 2021. The electricity generation from MSW does not include biomass-based energy production which accounts for an additional 10 GW of installed capacity. However, the cumulative power generation potential from natural and agro biomass across India is 42 GW (MNRE, India Statistics, 2020-21). In the next 20 years,

Table 3
Energy contents in various components of MSW.

Type of waste	Energy content (MJ/kg)			
	Nizami et al. (2015)	Brereton (1996)	Abdallah et al. (2018)	Akinshilo et al. (2019)
Mixed paper	15.82	11.63–18.61	15.816	15.804
Cardboard	NR	13.96–17.45	NR	NR
Mixed food waste	5.58	4.19–6.98	NR	5.58 (Organic Matter)
Mixed green yard waste	6.28	2.33–18.61	NR	
Mixed plastic	32.57	27.91–37.22	32.564	32.58
Rubber	26.06	20.93–27.91	NR	NR
Leather	18.61	15.12–19.77	NR	NR
Textiles	18.84	15.12–18.61	18.840	18.72
Wood	16.98	17.445–19.771	16.980	NR
Dirt, Ash, Brick	NR	2.33–11.63	NR	NR
Glass	NR	0.12–0.23	NR	NR
Metal	NR	0.23–1.16	0.697	NR
Organics	NR	NR	5.582	NR
Others	–	–	–	12.096

*NR Not Reported.

Table 4
Municipal solid waste management scenario in different states/Union Territory in India (Annual Report 2020-21 on Implementation of Solid Waste Management Rules, 2016).

Region	Solid waste generated	Collected	% Waste collected	Treated	% Waste treated	Landfilled	% Waste landfilled
	(TPD)	(TPD)		(TPD)		(TPD)	
Northern region	39 171.18	38 513.54	98.32	17 348.86	44.29	11 016.33	28.12
Western region	40 397.53	40 122.75	99.32	23 647.03	58.54	9859.89	24.41
Eastern region	25 256.19	23 845.77	94.42	3249.93	12.87	2587.44	10.24
Central region	9672.50	8885.50	91.86	8122.00	83.97	763.50	7.89
Southern region	45 541.50	41 381.89	90.87	27 588.48	60.58	5200.04	11.42
Total waste	**160 038.90**	**152 749.45**		**79 956.30**		**29 427.20**	

** **Northern Region States/UT:** Haryana, Himachal Pradesh, Jammu & Kashmir, Punjab, Uttarakhand, Uttar Pradesh, Delhi, & Chandigarh.
Western Region States/UT: Goa, Gujarat, Maharashtra, Rajasthan, Dadra and Nagar Haveli.
Eastern Region States: Arunachal Pradesh, Assam, Bihar, Manipur, Meghalaya, Mizoram, Nagaland, Odisha, Sikkim, Tripura, West Bengal, Jharkhand.
Central Region States: Madhya Pradesh, Chhattisgarh.
Southern Region States/UT: Andhra Pradesh, Karnataka, Kerala, Tamil Nadu, Telangana, Lakshadweep, Puducherry, Andaman and Nicobar Islands.
****Source:** Annual Report 2020-21 on Implementation of Solid Waste Management Rules, 2016. https://cpcb.nic.in/uploads/MSW/MSW_AnnualReport_2020-21.pdf

the projected potential of energy generation from urban waste alone is 1.12 GW of energy and by the next 30 years, this amount will increase by more than 100% (Malav et al., 2020; Cheng and Hu, 2010; Rao et al., 2010). Table 5 shows a comparison between the potential and installed capacities of WtE and biomass-based power plants in India.

3.3. Challenges to waste-to-energy projects in India

Many initiatives were taken previously to establish large-scale waste-to-energy recovery projects, however, many of them have failed. The first initiative was taken in 1987 wherein a 300 TPD solid waste processing capacity plant was set up in Timarpur, New Delhi. However, it had to close down within just six months. The plant was unable to operate profitably using the low calorific value of feedstock which had high inert materials content and high moisture content. Refuse-derived fuel plants i.e., a 6.6 MW (Megawatt) plant in Telangana, a 6 MW plant in Andhra Pradesh, and a plant in Chandigarh with 500 TPD capacity have been installed previously which have several operational difficulties. WtE plants having a 5 MW capacity in Uttarpradesh which was operational till 2017 are currently closed (MNRE, India Statistics, 2020-21). However, several of these have met with failures due to a plethora of reasons. According to the CPCB Annual report (2020–21), eastern India does not have any operational WtE facility despite contributing significantly to waste generation and having a higher percentage of landfilled waste (See Table 5 and Supplementary Table 1). Despite several challenges government of India is establishing several new WtE facilities across the country i.e., Andhra Pradesh, Haryana, Kerala, Madhya Pradesh, Manipur, Telangana, Rajasthan, Uttarakhand, etc. Hence, this section presents a detailed review of important factors that have led to the downfall of several previous WtE projects in India and steps/precaution that needs to be taken for the implementation of future projects in this sector.

3.3.1. Improper management of municipal solid waste and associated social stigma

To operate the waste-to-energy plants effectively, the waste has to be collected and segregated according to the requirements of the plant. India lacks the proper waste management standards that are necessary for proper functioning

Table 5
Energy recovery potential and current installed capacities for MSW and biomass based power plants in various zones of India (Data extracted from MNRE, India website).

Zone	Contributing states/UTs	Cumulative power generation potential from different MSW across India (MW)	Installed electricity generating capacity from MSW till March 2021 (MW)	Cumulative power generation potential from natural and agro biomass across India (MW)	Cumulative biomass power plants (Natural and agro-based residue) capacity installed till March 2021 (MW)
Northern	Haryana, Punjab, Delhi, Himachal Pradesh, Uttarakhand, Uttar Pradesh, Chandigarh	3653 (Excluding agricultural biomass power generation potential)	63.95	42 000 MW (42 GW) Biomass energy = 28 000 MW; Bagasse co-generation from Sugar Mill = 14 000 MW	2810.57
Central	Madhya Pradesh, Chhattisgarh		15.4		352.25
Western	Gujrat, Maharashtra, Rajasthan, Goa		12.93		2782.95
Eastern	Assam, Bihar, Jharkhand, Manipur, Meghalaya, Mizoram, Orissa, Tripura, West Bengal		Not Established		523.94
Southern	Andhra Pradesh, Karnataka, Tamil Nadu, Telangana, Pondicherry, Kerala	**Among them 1247 MW can be generated from Urban Solid Waste	76.36		3545.99
		Total	**168.64 MW**	**Total**	**10 015.7 MW (10.01 GW)**

Source: Ministry of New and Renewable Energy, India Website Data extracted from 2020–21 statistics (https://mnre.gov.in/bio-energy/current-status). For Individual Solid Waste Type wise Power Generation Potential, See **Supplementary Document 1**.

and continuous supply of quality feedstock required for WtE plants. There is a dire need for proper dumping bins in every household, and locality, proper collection (both urban and rural areas), and segregation of waste hygienically. Both skilled operators and workers are required in these plants. However, such jobs in India are looked down upon. This kind of social stigma and backward perspective of the people needs to change and proper steps should be taken towards raising the dignity of these workers and raising social awareness. There is a necessity for more financial inputs from the centre and state governments to develop proper waste management infrastructure (Malav et al., 2020).

3.3.2. *Lack of proper financial investment and political issues*

In India, the policies regarding waste-to-energy and emission-related standards are not comparable to European and global standards. This creates a reason for the reluctance among the stakeholders to be associated with this sector. The majority of Indian solid wastes have low calorific values (wet waste) and to function profitably, a basic incentive per ton of waste treated and additional subsidies are necessary. The stakeholders also have a concern regarding a continuous supply of MSW for recycling and energy generation without continuous support from the central/state government and local municipal bodies. Due to political interference, there is very less coordination between the public and private investing entities, thus making risk mitigation difficult and subsequent project failure. The government stakes in all previous projects have been very low as it tries to avoid sharing the financial risks. This again shows a lack of confidence in the government in its waste management initiatives. Moreover, the financial allocation from the central government to the state bodies is quite less and there have been many complaints from the urban local bodies (ULB) regarding this matter. This prevents them from undertaking expenses for proper MSW collection and segregation (Malav et al., 2020; Nixon et al., 2017).

3.3.3. *Lack of regulations and implementations of policies*

There have been instances where the workers responsible for collecting the waste have deliberately mixed hazardous or contaminated industrial wastes with normal residential wastes to increase the weight of the wastes collected to receive higher pay. This kind of unethical behaviour is the direct result of the negligible enforcement of laws regarding solid waste management (Nixon et al., 2017). Air emission standards in India are more lenient compared to global standards. Many critical air quality indicators like Total Organic Carbon (TOC), Hydrogen Chloride (HCl), Carbon Monoxide (CO), Sulphur

Dioxide (SO_2), Heavy Metals, Dioxins, and Furans are not reported by Indian WtE plants (Nixon et al., 2017). Air emission standards for the WtE plant do not require them to report these parameters. It shows the lack of necessary regulations to mitigate air pollution hazards of such plants on the local population.

3.3.4. Conflict of public interests

The reasons for public resentment towards incineration plants were surveyed in Delhi (Demaria and Schindler, 2016). It showed that there were mainly two kinds of conflicts in public interests. First were for those people who lived their lives by earning money from collecting waste and then selling it. After the introduction of proper waste collecting systems, their livelihood was taken away from them and they had no alternative income option. The second kind of conflict was for the residential people near the WtE plant's location. They could not bear the pungent smell emanating from the incineration plants and the health hazards associated with the plant emission. All these factors forced residents to lodge legal complaints regarding the same which further hinders the operation of such plants and adversely influences public opinion.

3.3.5. Lack of indigenous technological advancements

India lacks technological developments in terms of waste-to-energy plants. Current WtE technologies are designed to treat European and American wastes which contain less moisture (20%–25%) contrary to Indian wastes which have higher moisture content (40%–50%). Hence, India needs to develop indigenous technologies, which can specifically cater to the needs of Indian waste (wet organic waste). Other technological disadvantages include high costs of operation as well as a lack of experienced operators and technicians (Nixon et al., 2017).

4. Comparative analysis of global WtE standards with the Indian scenario

European cities like Vienna, Berlin, Amsterdam, Munich, Zurich, etc are considered the best cities for living in terms of quality of life, the beauty of nature, and greenery. These kinds of results were achieved only because European cities give great importance to solid waste management and waste-to-energy conversion technology (Chaliki et al., 2016). The European wastes have lower moisture content (about 20% to 30%) as compared to Indian MSW (about 40% to 50%) (Kumar et al., 2022; Ranjith Kharvel Annepu Advisor and Themelis Stanley-Thompson Professor Emeritus, 2012). This is a major factor in why waste incineration plants in India incur heavy financial losses in many cases.

It has been recorded that the average MSW generation per capita decreased in European countries from 520 kg/capita in the year 2008 to approximately 475 kg/capita in 2012 (Persson and Münster, 2016). According to the terms of directives of the Austrian landfill, it was prohibited to landfill any wastes which have more than 5% of organic carbon content without prior treatment. Hence, special waste management methods like waste separation at source and Mechanical–Biological Treatment (MBT) are used to follow the directives (Chaliki et al., 2016). This is in absolute contrast to the Indian scenario, where most of the states treat less than 10% of the total waste collected (Malav et al., 2020). It has been found in many European countries that; a major portion of waste management is performed using landfilling. However, some countries like Germany, Netherlands, Belgium, Sweden, Denmark, and Austria have maintained landfill at less than 5% (Chaliki et al., 2016; Cucchiella et al., 2014). This has been depicted in Table 6 which shows the percentage of wastes that are recycled, combusted, and go into landfills, in a few European cities. It can be noticed the percentage of landfill in these cities is significantly less. The situation in Delhi is exactly the opposite compared to those of European cities where the majority of waste goes into landfill sites. As the Indian population and per capita waste generation grow in the next few decades, landfill sites will be entirely exhausted and the need for alternative waste management strategies will gain impetus. Therefore, WtE plants based on different thermochemical & biochemical technology will become an integral part of urban and rural infrastructure. Annepu et al. (Kumar et al., 2022; Ranjith Kharvel Annepu Advisor and Themelis Stanley-Thompson Professor Emeritus, 2012) predicted per capita waste generation to reach 0.649 and 0.741 kg/day by 2031 and 2041, respectively. This also indirectly indicates the energy generation potential from waste.

It has been also observed in many cases that the countries which prioritize waste-to-energy conversion lack recycling rates and may see a fall in the amount of waste recycled over the years. However, it is the opposite in the case of countries in Europe. The EU has advanced technologies for waste-to-energy conversions and at the same time, it has one of the highest recycling rates in the world (Chaliki et al., 2016). EU gives a higher preference to reuse and recycling over other treatment options. Then comes composting, incineration, and finally if there is no other option then landfilling is done. The European Union's waste framework directive (which is the current legislation), aims at achieving a 50% recycling or processing by reuse target by the end of 2020 (Persson and Münster, 2016). Currently, the incineration process is the most dominant waste management method used in Europe. Recently, there have been huge investments in newer technologies, like sorted fractions, which have slowed the progress of newer incineration plants. Newer technologies aim to decrease the amount of waste storage and hence decrease the final waste volumes that go into landfills (Münster and Meibom, 2010).

Table 6
Waste treatment comparison between some European cities and the electricity generated by them (Bhawan and Nagar, 2022; Chaliki et al., 2016; Naveen and Sivapullaiah, 2020).

City	Population (Millions)	Waste recycled (%)	Waste composted (%)	Waste combusted (%)	Waste going into Landfills (%)	Electricity generated (MWh/ton of waste)
Munich	1.4	44	6	49	1	0.41
Berlin	3.4	50	10	40	0	0.39
Greater Copenhagen	0.9	62	4	25	9	0.49
Malmö	0.67	20	6	69	5	0.46
Zurich	0.39	29	9	62	0	0.45
Vienna	1.67	23	11	63	3	0.16
Mallorca	0.87	13	19	44	24	NR
Delhi	21.39	NR	47.5% (Treated)		52.5	0.0053
Bangalore	13.09	26.72% (Treated) (10% Recycled)			73.28	NR

Bangalore Statistics were taken from Bruhat Bengaluru Mahanagara Palike Website (https://site.bbmp.gov.in/departmentwebsites/swm/).

5. Identification of major air pollutants produced during WtE processes and the strategies for their removal from the flue gas stream

Flue gases and residues of combustion are the main sources of air pollutants from WtE facilities. Additionally, air pollution can also be caused by the emissions from the waste/trash that is stacked in WtE facilities, emissions during the transportation of solid waste from WtE plants to landfills, and emissions due to the production of value-added chemicals. When the waste management infrastructure is small in size/capacity, it may have lower efficiency and as a result, the emissions during the energy conversion processes may increase (Consonni et al., 2005). The types of air pollutants generated depend on the type of process and nature of MSW which is used by the WtE plant. The pollutants can be categorized into many types such as particulate matter, acid gases, greenhouse gases, NOx, volatile organic compounds (VOCs), persistent organic pollutants (POP), mercury, heavy metals, etc. In most cases, these emissions can be minimized to a great extent by using air pollution control devices and by removing pollution precursors like chlorine and nitrogen (using gas pre-treatment) (Belgiorno et al., 2003).

The flue gas emitted from the combustion chamber after the process of energy conversion contains a high concentration of air pollutants. To decrease the concentration and number of air pollutants, several technologies are used in sync. The first process in this sequence of air pollution abatement is usually the removal of fly ash. Next, use various processes to neutralize acid gases. Finally, dioxins, mercury, and heavy metal removals take place (Vehlow, 2015). Table 7 sheds light on major air pollutants, and their key properties and also discusses different air pollution control systems and their removal mechanisms.

6. Health hazards caused by exposure to emissions from WtE plants

Several studies related to the human health effects of air pollutants show the role of feedstock type, country-specific emissions data/standards (Cole-Hunter et al., 2020), and operating conditions on the risk assessment outcomes. A report concluded that the higher the operational age of the plant greater will be the risk of exposure to toxic carcinogenic pollutants like chromium (Cr), cadmium (Cd), nickel (Ni), arsenic (As), polycyclic aromatic hydrocarbons (PAHs), and dioxins (which are lipophilic, i.e., tend to concentrate in highly fatty tissues) (Cole-Hunter et al., 2020; Rushton, 2003). The accident in Seveso showed adverse effects on liver function due to high exposure to 2,3,7,8-TetraChloroDibenzoDioxin (TCDD) (McKay, 2002).

Depending upon the levels and duration of exposure, various human organs/systems like the central nervous system, lungs, skin, livers, kidneys, reproductive system, etc. may be affected. Chronic health problems like reduced functioning of the lungs, lung cancer, bronchitis, and an overall reduction of human lifespan, may occur even at lower concentrations if the duration of exposure is long enough (Rushton, 2003). Studies in California have indicated that with an increase in the dumping of hazardous wastes at disposal sites, cases of lower birth weights and neonatal deaths showed an increasing trend (Rushton, 2003). Another study showed that emissions from landfills are significantly more harmful in terms of both cancer and non-cancer risks when compared to WtE incineration facilities. This is due to the contamination of groundwater from leachate. A study in Slovakia found that the risk of cancer was increased by 10–80 folds if the MSW incineration was conducted in the open air (Cole-Hunter et al., 2020). Problems like respiratory symptoms, fatigue, allergies, irritation of the eyes, nose, skin, and gastrointestinal problems were reported in nearby residents (mainly children, elderly, and asthmatics), however, the results obtained by the investigation were inconclusive. The stress of exposure was found to be a major aggravator of health issues (Rushton, 2003).

Furthermore, a study conducted in Taiwan concluded that there was a negative effect on children whose residences were within 3 km of the incineration plant and the effect was most visible in the age group of 6 to 18 months (Cole-Hunter et al., 2020). The workforce employed for collecting, sorting, and recycling is at a greater risk of exposure than others.

Table 7
Brief description of the common air pollutants generated in WtE processes and their removal strategies.

Pollutant	Key features of pollutant	Removal techniques	Primary characteristics of removal methods
Particulate matter		Dust separators	
Dust	• Inorganic dust particles remain in the air after combustion. • These escape from the furnace by remaining suspended in flue gases. • Gaseous compounds (metal chlorides, volatile heavy metals, dioxins, and furans) condense on these particle surfaces and hence residues from the APC units are categorized as hazardous wastes (Pařízek et al., 2008; Quina et al., 2011).	Cyclone separators	• Particle-loaded gas enters a cylindrical chamber tangentially with a high initial speed. • The mechanism of separation of fly ash is an inertial effect. • Maximum efficiency is 90% for 15 µm particles (Cortés and Gil, 2007). • Activated carbon-based dust separator for particulate matter removal (Duran and Caldona, 2020).
		Electrostatic precipitators	• The underlying separation mechanism is electrostatic force. • The main components are a set of oppositely charged metal plates (kept parallel to each other), through which the gas passes at low velocity. (Corona Discharge). • Removal efficiency for 10 µm particles exceeds 99.5 percent (Vehlow, 2015).
		Fabric filters	• Raw gas passes through bags of temperature-resistant fabric which are supported by metal cages. • Fly ash needed to be separated, and stays on the surface while pulses of air blow it off periodically (Vehlow, 2015). • Particles from the discharge hopper are released by washing. • Removal efficiency for $PM_{2.5}$ is in the range of 99.37% to 99.91% (Xu et al., 2016).
		Venturi scrubbers	• Water is initially sprayed on the flowing flue gas in the throat section of the equipment. • Particles get isolated upon collision due to the velocity increase caused by the convergent tube. • Commonly used due to their strong ability to distinguish particles through inertial effects. • Particles of size 0.5 to 10 µm can be easily removed (Pak and Chang, 2006).
Abatement of acid gases		Removal methods for acid gases	
Sulphur Dioxide (SO_2)	• Released when sulphur containing MSW (either organic or inorganic) oxidizes during the combustion process (Quina et al., 2011). • Reaction: $C_xH_yS + w\ O_2 \rightarrow CO_2 + H_2O + SO_2$	Wet scrubbing systems	• Absorb acid gases from gas mixtures by adding specific agents which neutralize each acid. • Two-phase process – acid scrubbing of hydrogen halides followed by acid separation of SO_2. • Absorption efficiency depends on the contact surface and is paired with other devices for higher efficiency (Vehlow, 2015).

(continued on next page)

It was suggested that they are prone to skin, respiratory, and gastric problems due to continuous exposure to volatile organic compounds and bioaerosols (Rushton, 2003). Table 8 summarizes the toxicological and human health impacts of air pollutants released from WtE plants.

Table 7 (*continued*).

Acid chlorides and fluorides	• Cl and F in MSW get converted into acidic hydrogen halides or chlorides and fluorides of heavy metals like zinc (Zn) and lead (Pb). • Chlorine in MSW mostly comes from salty foods and plastic waste like PVC pipes. • Sources of fluorine include plastics such as Polytetrafluoroethylene (PTFE) and textiles that are fluorinated (Hu et al., 2018; Ma et al., 2020).	Dry scrubbing Systems	• A vigorous reaction between the pollutants and the slurry is performed in a single step. • Dry scrubbing, semi-dry scrubbing, and semi-wet scrubbing are the three alternatives. • Ca or $NaHCO_3$-based systems are the most common (Vehlow, 2015). • Products are accumulated using baghouse filters, on the surface of these filters neutralization reactions occur.
Green House Gases (GHGs)	• Released during combustion of organic matter present in the MSW. The moisture content of MSW influences the type of air pollutant emissions. • The most common GHG emissions are CH_4, CO_2, NO_2, HF_6 (Sulphur Hexafluoride), PFC (Perfluorocarbons), and HCF (Hydro Fluorocarbons). • A large amount of GHG emissions can be prevented by shifting the dumping of wastes in landfill to WtE plants (Wang et al., 2017).	Microalgae based bioreactors	• Algae like Spirulina are capable of reducing CO_2, NO and SO in polluted air and can also produce O_2. • The system consists of a culture tank, an air supply unit, and a lighting source/unit. • Photosynthesis of algae turns CO_2 into O_2 and the algae use NO and SO as nutrients, thus making the overall process quite efficient (López et al., 2013; Yen et al., 2015).
NO_x		Removal methods of NO_x	
Oxides of Nitrogen (NO_x)	• When NOx is produced from nitrogen in the air, it is called thermal NO_x. • When NOx is produced from nitrogen in waste, it is called fuel NO_x. • When NOx is produced from organic compounds, it is called prompt NO_x. • Usually, thermal NO_x is produced in higher quantities compared to fuel NOx, while prompt NO_x is produced in the least amount (Quina et al., 2011).	Selective catalytic reduction (SCR)	• Catalysts used are deactivated in a highly acidic medium. • Catalytic reduction (at a certain temperature) is performed after the removal of PM from flue gases. • Operating condition: 200 °C-400 °C, in the presence of ammonia (In fixed bed reactor) • Despite higher investment costs, higher pressure drop, and high O_2 requirements, removal efficiency only ranges between 50%–80% (Quina et al., 2011).
		Selective Non-Catalytic Reduction (SNCR)	• Utilizes ammonia (NH_3) as a reactant or urea ($CO(NH_2)_2$) as a reducing agent for smaller systems, which gets injected directly into the furnace. • Urea decomposes and forms ammonia at high temperatures. Hence, reducing reactions occur between 850 °C to 1050 °C. • Benefits include lower investment costs and lesser corrosion problems. • Has a lower removal efficiency than SCR (Quina et al., 2011).
Persistent organic pollutants		Removal of persistent organic pollutants	

(*continued on next page*)

7. Environmental impact assessment of various WtE plants over landfill

The impact of WtE plants on the environment can be categorized based on the type of research being conducted. Factors like global warming potential (GWP), acidification potential, abiotic depletion, photochemical ozone creation potential, human toxicity potential, and terrestrial eutrophication are widely used for environmental impact assessment studies (Evangelisti et al., 2015; Khoo, 2009). Few researchers also consider factors like "human health", "ecosystem quality", and "resources" to compare the pros and cons of emissions from incineration plants over landfill sites. All the environmental

Table 7 (*continued*).

Dioxins and Furans	• Considered hazardous substances by WHO. • The possible positional isomers of dioxins and furans are 75 and 135, respectively. • This number depends upon the location of chlorine (Cl) attachment on a benzene ring (Quina et al., 2011). • Formed as by-products in trace amounts when H_2, O_2, C, and Cl are exposed to heat (McKay, 2002).	Adsorption method	• Flue gases are cleaned by adsorption using activated carbon as the adsorbent. • It is then sprayed along with a suspension of lime in a spray chamber. • Heavy particles (i.e. Hg), are detained over the exterior of the activated carbon. • Though a notable reduction in the amount of dioxin is achieved, it produces large quantities of hazardous wastes (Pařízek et al., 2008).
Mercury (Hg)	• Produced from household products like fluorescent lamps, alkaline batteries, thermometers, button cells, etc. (Hu et al., 2018). • Highly toxic substance and generally present in liquid-state at room temperature • It becomes volatile and mixes with the flue gases at a temperature of 357 °C. • Commonly exists in the form of HgO or $HgCl_2$, (Quina et al., 2011).	Catalytic filtration	• Fly ash is removed using filter bags which are cleaned regularly using pulse jets. • Breaks down dioxins as the flue gas passes through them. • The Polytetrafluoroethylene layer filters out 95% of hazardous particles, and 98.8% efficiency is attained by using catalysts. • Reduces the cost of increasing flue gas temperature and remains operational over a long time (thus cutting the annual cost considerably) (Pařízek et al., 2008).
		Combined NOx selective catalytic reduction (SCR) and dioxins destruction	• Catalytic decomposition of dioxins occurs at a temperature of 200–300 °C in a catalytic reactor using NH_3. • Simultaneous degradation of NO_x and dioxins allows the flue gas to be reheated to the temperature needed for the reaction to occur in the DeNOx/DeDiox reactor (Pařízek et al., 2008). • Carried out after mechanical and chemical cleaning of flue gases to avoid catalytic poisoning.
VOCs		Methods to remove VOCs	
Volatile Organic Compounds (VOCs)	• Consists of carbon chains or rings like ethane, propane, benzene, toluene, etc. • Mainly formed due to incomplete combustion (Hu et al., 2018). • The health of people living both near and far away from the source of emissions and the environment is negatively impacted (Koppmann et al., 2005).	Thermal or catalytic oxidation	• In thermal oxidation, VOCs are first heated to 800–1100 °C. • Thermal oxidation can be done with either dry oxygen or using oxygen and water vapour (Lewandowski, 2017). • In thermal oxidation, up to 99% of the VOCs are removed at temperatures above 1000 °C. (Kamal et al., 2016). • Catalytic oxidation occurs at lower temperatures, usually 250–500 °C (Kamal et al., 2016). • Catalytic oxidation is a more energy-efficient process than thermal oxidation (Kamal et al., 2016). • The catalysts involved can be both homogeneous and heterogeneous.
Heavy metals		Removal methods for Heavy Metals	

(*continued on next page*)

impacts were calculated by considering certain factors and then those values were normalized according to national standards depending on individual countries (Morselli et al., 2008).

A UK-based study on various two-stage combination plants like the gasification-plasma process, fast pyrolysis-combustion process, and gasification-syngas combustion process, found that the gasification-plasma plants had the least

Table 7 (*continued*).

Other heavy metals	• Antimony (Sb), Arsenic (As), Chromium (Cr), Vanadium (V), Cadmium (Cd), Manganese (Mn), Nickel (Ni), and Lead (Pb) are some of the heavy metals. • Highly toxic and carcinogenic. They can cause severe respiratory problems. • Sources include Ni-Cd batteries, Cd- stabilized plastics, etc.	Coagulation–flocculation	• Alum (Aluminium Sulphate) (optimum pH = 6.5) and Ferric Chloride ($FeCl_3$) (optimum pH = 10) are used as potential coagulants (Zazouli and Yousefi, 2008). • The removal efficiency of heavy metals using alum and $FeCl_3$ are 77%–91%, and 68–85.5%, respectively (Zazouli and Yousefi, 2008). • The most effective coagulant doses for heavy metal removal are found to be 1400 mg L^{-1} and 1000 mg L^{-1}, respectively for alum and ferric chloride (Zazouli and Yousefi, 2008). • $FeCl_3$ is more economical as compared to Alum.

Table 8
Health and toxicological effects of air pollutants released from WtE plants.

Sl. No.	Name of the waste-to-energy process	Pollutants from WTE plants	Health impacts of pollutants	Toxicological effect of pollutants	References
1	Incinerators	Particulate matter size greater than 10 $\mu g/m^3$	Bronchitis, Asthma, Emphysema, Pneumonia, and cardiac disease	• 1% increase in mortality for a 10 mg/m^3 increase in PM. • Respiratory mortality is up by 3.4%. • Cardiovascular mortality is up by 1.4%.	Criteria Air Pollutants, US EPA Website (2022)
2	MSW burring Incinerators	$PM_{2.5}$ size less than 2.5 μm	Serious health effects in alveolar/gas exchange region	• Toxic or Carcinogenic: Pesticides, Lead, Arsenic, radioactive material • 8% Increase in lung cancer for every 10 $\mu g/m^3$ increase in $PM_{2.5}$	Criteria Air Pollutants, US EPA Website (2022)
3	Incinerators	Nitrogen Oxide (NO_x)	Nose and eye irritation, Lung tissue damage, Pulmonary Edema, Pneumonia	Pulmonary fibrosis, emphysema, and higher lower respiratory tract illness in children	Criteria Air Pollutants, US EPA Website (2022), Shimizu et al. (2007)
4	Incinerators burning sewage and hazardous waste sludge	Sulphur Oxides (SO_X)	Broncho-constriction, Ear/Nose/ Throat, irritation, Mucus secretion	Respiratory illness Aggravates existing heart disease	Liang et al. (2021)
5	Incinerators burning fuels that contain lead (phased out), metal processing, waste incinerators, lead smelters, lead paint	Lead (Pb)	Absorbs in blood, Damages organs – kidneys, liver, brain, reproductive system, bones (osteoporosis)	• Accumulates in blood, bones, muscles, fat • Increases learning disabilities Young children • Increased heart disease and • Chronic poisoning	Lead poisoning (2022)
6	Municipal solid waste incinerators	Chlorinated dibenzo-p-dioxins	Absorbs in skin	Reproductive and developmental effects Chloracne	Ruokojärvi et al. (2004) Wei et al. (2021)
7	Municipal solid waste incinerators	Chlorinated dibenzofurans (CDFs)	Absorbs through skin	Skin toxicity, Immunotoxicity, neurotoxicity, teratogenicity, endocrine disruption, and a predisposition to cancer.	Loganathan and Masunaga (2009) Wei et al. (2021)
8	Municipal solid waste incinerators	Polychlorinated biphenyls (PCBs)	Absorbs through skin	Liver problems, Elevated blood lipids	Ruokojärvi et al. (2004)
9	Biogas plants	Methane	Inhalation through nose	Results in mood changes, slurred speech, vision problems, memory loss, nausea, vomiting, Increase in heartbeat rate	Paolini et al. (2018)

Global Warming Potential (GWP) compared to other technologies (Evangelisti et al., 2015). It was also found that landfills were the highest contributor to GWP and methane emissions from landfill sites have 25 times stronger global warming potential than CO_2. The study showed that the acidification potential of incineration plants was 10 times higher as compared to the gasification-plasma plants. This is attributed to the higher electricity production efficiency of the latter compared to the former. The study concluded that the emission of gases like volatile organic compounds (VOCs), oxides of nitrogen (NOx), and carbon monoxide (CO) are higher in landfills; and it has a very high photochemical ozone creation potential (POCP) (Evangelisti et al., 2015).

A Singapore-based study concluded that the highest contributor to their global warming potential is the gasification of scrap tyres and pre-treatments are necessary for granulated MSW-based WtE plants (Khoo, 2009). The conversion of MSW to refuse-derived fuel (RDF) and its gasification contributed to the largest amount of acidification potential. Circulating Fluidized Bed (CFB) gasification contributes to the largest amount of terrestrial eutrophication and photochemical ozone formation. A study in Northern Italy (Morselli et al., 2008) concluded that landfills have the highest impact on categories like resource consumption (due to land usage and transportation of incineration residues to landfill) and ecotoxicity. Landfilling has more impact on ecotoxicity compared to incineration due to the underground dispersion of heavy metals into groundwater which has the potential to cause significant damage to the ecosystem. WtE plants can reduce GHG (greenhouse gases) emissions when compared to landfills by 1 ton of CO_2 per ton of waste combusted (Chaliki et al., 2016).

As pointed out by various research groups, landfills are more hazardous than incineration plants in most of the impact categories (Tan et al., 2014). It takes more time for the effects of landfills to be visible, and hence it is a common belief that incinerations have a worse impact. It has to be pointed out that a large number of impacts can be negated just by using proper recycling and sorting methods for MSW (Ionescu et al., 2013). The best way to reduce the environmental impacts would be to use a combination of strategies like recycling materials, incineration of dry wastes, and then using a biological treatment on the residues before transportation to landfills rather than directly dumping them in landfills (Chaliki et al., 2016). Environmental impact assessment studies from the Indian context (on Indian WtE plants) are significantly lagging which requires more attention from researchers working in this domain.

8. Selection of best strategy for WtE conversion

Several factors need to be considered while selecting the most suitable Waste-to-Energy conversion process. Factors affecting the cost-effectiveness of a waste-to-energy cogeneration plant vary due to several technical parameters such as plant capacity, the calorific value of feed waste, economical parameters i.e. credit requirements, cost of cleaning up flue gas, cost of disposing off residue, and hazardous waste, revenue from the sale of electricity and heat, high ash content and the cost of selling electricity and heat (Schneider et al., 2010). The type of air pollution control (APC) system used greatly affects the initial setup cost, and the operation costs, and determines the future revenue. The prime focus of any WtE plant should be to increase energy output and minimize pollutant emissions. However, in the Indian scenario, many WtE plants neglect the government-imposed emission standard due to the high cost associated with setting APC units (Nixon et al., 2017). Another important factor is the country in which the WtE conversion strategy is being planned. For example, the economic benefit of the plants depends on the policies of the country like incentives, gate fees, and the price of energy in that region (Wang et al., 2016).

In a simplified life cycle cost comparison analysis, it was concluded that the CFB (Circulating Fluidized Bed) gasification of organic waste and the combined pyrolysis, gasification, and oxidation of MSW are the two most cost-effective waste-to-energy conversion systems (Khoo, 2009). Thermal cracking gasification of granulated MSW and gasification of tyres are the least favoured WtE methods due to their negative environmental effects and high operational costs (Khoo, 2009). Pyrolysis-gasification of MSW and steam gasification of wood are the most environmentally friendly route, whereas CFB gasification of organic waste, followed by combined pyrolysis, gasification, and oxidation of MSW is the most cost-effective (Khoo, 2009). It has been concluded in another study that pre-treatment before combustion decreases the absolute cost of thermal treatment. The cost of waste pre-treatment is often high. However, the benefits of improving feedstock quality at the WTE facility do not outweigh the costs of doing so (Consonni et al., 2005). In terms of the payback period, the internal rate of return, and the profitability index, the incineration approach is more financially favourable, primarily due to the high volume of waste it can process. Anaerobic digestion (AD), on the other hand, is significantly affected by the cost of landfilling and the price of digested products (Abdallah et al., 2018). From the Indian context, the biochemical process (AD and fermentation) and thermo-chemical processes like gasification, pyrolysis, or a combination of both strategies are the most suited for WtE production due to the higher moisture and organic matter content in the waste.

9. Need for strict government regulation and monitoring

According to National ambient air quality standards in India (under the Environmental (Protection Act), limits for stack emissions only exist for normal incineration plants, while a national emission standard for MSW incineration plants has not been framed yet. These WtE plants thus have to abide by the operating certificate agreement issued by the respective state governments in India. In several states, the emission standards are very lenient. A comparison of the emission standards of Europe, the United States, China, Japan, and India (Ecopolis, New Delhi & Shalivahana, Telangana) is provided in Table 9.

The number of air emission parameters to be monitored in the Indian WtE plants is very less. For example, there is a plant in Karimnagar, Telangana (Shalivahana Green Energy Ltd.) that monitors only particulate matter (PM), oxides of

Table 9
Emission standards of the European Union, USA, China, Japan, and India (Dong et al., 2018; Hu et al., 2018; Nixon et al., 2017; Ranjith Kharvel Annepu Advisor and Themelis Stanley-Thompson Professor Emeritus, 2012).

Emissions	Europe	China	USA	Japan**	India (Ecopolis, New Delhi)	India (Shalivahana, Telangana)
Particulate Matter (mg/m^3)	10	20	25 (3-run avg.)	NR	150	100 (PM_{10}) 60 ($PM_{2.5}$)
Sulphur Dioxide (SO_2) (mg/m^3)	50	80	29	10–30	N/A	80
Nitrous Oxides (NO_x) (mg/m^3)	200	250	165–250	30–125	450	80
Total Organic Carbon (TOC) (mg/m^3)	10	NR	NR	NR	N/A	N/A
Carbon Monoxide (CO) (mg/m^3)	50	80	50–250	50	N/A	N/A
HCl (mg/m^3)	10	50	29	15–50	50	N/A
Mercury (Hg) (mg/m^3)	0.03	NR	0.05 (3-run avg.)	0.03–0.05	N/A	N/A
Heavy metals (mg/m^3)	0.51	NR	NR	NR	N/A	N/A
Dioxins/furans (mg TEQ/N m^3)	0.11	0.1	30 or 35 (total mass basis)*	0.1	N/A	N/A

* The limit is 30 ng/N m^3 and 35 ng/N m^3 for non-ESP-equipped and ESP-equipped units respectively.
** 273 K, 101.3 kPa, 14 vol% CO_2.
*** Daily avg. values (if not stated otherwise).
NR = Not Reported, N/A = Not Applicable for Air Emission Standards (in India).

sulphur (SO_x), oxides of nitrogen (NO_x), carbon dioxide (CO_2) and oxygen (O_2). Other major pollutants like VOCs, POPs, heavy metals, and mercury are not monitored. In a plant in New Delhi (Ecopolis), the PM emission limits are 10 times higher than that in the UK and the emission data that is measured comes out to be 100 times higher than the UK-based plant (Nixon et al., 2017).

In 2000, the Ministry of Environment and Forests (MoEF), Government of India released guidelines for scientific MSW management, ensuring the proper collection, separation, transportation, processing, and disposal of MSW as well as upgrading existing facilities to reduce the pollution of soil and groundwater. The Central Pollution Control Board (CPCB) serves as an authority and is the body to which municipalities are required to send annual reports. In addition, the states themselves have released Municipal Corporation Acts, which further deal with the environmental damage caused by inappropriate MSW management techniques (Kalyani and Pandey, 2014). To comply with the MSW rules, municipalities require to adopt proper collection, segregation, processing, and disposal of MSW, and adequate waste management infrastructure should be established.

In these aspects, the central the state governments of India have a poor degree of cooperation. The requested data is sent with delay from the state to the central government, leading to delays in carrying out effective ground-level measures. The key challenge is perceived to be the lack of cooperation with the urban local authorities for a clearly defined action plan and inadequate implementation strategies. Boosting public knowledge and awareness regarding MSW management issues has never been taken seriously by local and central authorities (Malav et al., 2020). For MSWI which are not hazardous, emission limits need to be standardized and updated. Many residents residing close to WtE facilities reported that plants were violating emission limits and counterfeiting data (Nixon et al., 2017). However, the issues of creating public awareness concerning waste management have changed significantly improved in the recent past through several governmental initiatives like Swachh Bharat Mission and Ban on single-use plastics. On the other hand, the government needs to implement stringent laws on emission standards and should regularly monitor WtE plants to check whether they are abiding by the standard. The emission data should be available in the public domain to create more transparency and improve public perception of such energy generation methods.

10. Conclusion

With the ever-increasing demand for energy in a rapidly growing economy like India, cheap and sustainable energy is the need of the hour. Waste to Energy conversion remains a major untapped energy resource in the Indian context. Several efforts have been made by the government of India to improve our waste energy potential (biomass, MSW). A significant improvement in biomass energy generation capacity (10 GW) has been attained in the past decade, however, the MSW-based energy potential is yet to be realized. It is to be mentioned that less than 5% of the overall energy generation potential from MSW is currently utilized in India. The present review has aimed to address the currently available technology relevant to Indian WtE sectors, and their advantages and limitations. The review also provides information on installed electricity generation capacity from WtE in different parts of India and sheds light on the overall energy potential. The study highlights the differences between the global and the Indian WtE scenario. The study devotes significant attention to identifying and suggesting mitigation strategies for air pollution hazards of WtE plants. The review also includes a discussion on environmental impact assessments of WtE technologies. In this paper, the key factors which are needed to be considered while building/planning a WtE plant have been reviewed and the best plant options have been suggested in various scenarios based on cost-effectiveness and environmental friendliness. Several challenges and roadblocks preventing the successful implementation of several Indian Waste to Energy projects have been presented. The key findings from the review are listed below:

- Waste incineration is an unsuited WtE method for the Indian scenario due to a lack of waste segregation and a higher percentage of wet waste over dry waste. Higher moisture content (50%) in Indian solid waste compared to European and American wastes (20%–25%).
- Indian WtE sector is far from reaching its MSW energy potential of 3653 MW. Currently only produces 168.64 MW of electricity. Southern and Northern regions of India are the biggest contributors whereas western and central regions contribute significantly less. Currently, the eastern region does not have any operational MSW-based WtE plants as per the latest MNRE report. In the eastern region, a higher percentage of waste goes to landfill sites where implementation of WtE projects has become a necessity (See Supplementary Table 1).
- Biochemical-based (anaerobic digestion and fermentation) and thermo-chemical WtE methods (gasification/pyrolysis) are the most suitable techniques considering the physical and chemical properties of Indian solid waste as it contains a large percentage of biodegradable, wet, and organic waste.
- The major pollutants released from WtE plants are identified i.e., particulate matter (dust), acid gases (sulphur dioxide, acid chlorides, fluorides, and oxides of nitrogen), greenhouse gases (CH_4, CO_2, Sulphur Hexafluoride, Perfluorocarbons, and Hydro Fluorocarbons) volatile organic components (ethane, propane, benzene, toluene), persistent organic pollutants (dioxins and furans), and heavy metals (Mercury (Hg), Antimony (Sb), Arsenic (As), Chromium (Cr), Vanadium (V), Cadmium (Cd), Manganese (Mn), Nickel (Ni), and Lead (Pb)). The study also identifies suitable air abatement technologies i.e., cyclone separator, ESP, fabric filter, venturi scrubbers, dry & wet scrubbing, microalgae bioreactor, selective catalytic reduction, adsorption, catalytic filtration, thermal or catalytic oxidation, coagulation–flocculation, etc. to deal with such pollutants (See Table 7).
- Air pollutants from WtE plants have significant health and toxicological effects on humans. Several illnesses like respiratory, cardiovascular, cancer, skin–nose irritation and kidney–liver–brain damage are caused by these air pollutants (See Table 8).
- Significant roadblocks preventing the successful implementation of several Indian Waste to Energy projects are the lack of strict government regulations as well as multiple environmental, financial, and logistical issues, negative public perception, and major air pollution concerns. Poor waste segregation at the source and higher moisture content in waste also significantly reduces its feasibility.
- From the air pollution data reported in existing literature/government reports, it can be seen that the government is very lenient concerning the emission standards of WtE plants in India. Many WtE plants established throughout the country do not report several crucial parameters like SO_2, total organic carbon, heavy metal, and dioxin–furan concentration (See Table 9). In several cases, air pollution data far exceeds the government-imposed emission standards.

This review article helps to illuminate the different factors critical to the success of Indian WtE projects. Despite several challenges and health-related concerns associated with WtE plants in India, the authors reiterate the importance of such projects both in terms of energy security and effective solid waste management. The authors hope that the researchers and engineers working on WtE projects in India would agree with the aforementioned findings.

CRediT authorship contribution statement

Arijeet Karmakar: Conceptualization, Methodology, Data curation, Writing – original draft. **Trisha Daftari:** Methodology, Data curation, Writing – original draft, Editing, Visualization. **Sivagami K.:** Formal analysis, Writing – review & editing, Supervision. **Mohammed Rehaan Chandan:** Data curation, Writing – original draft. **Aabid Hussain Shaik:** Writing – original draft, Editing, Visualization. **Bandaru Kiran:** Writing – original draft, Formal analysis. **Samarshi Chakraborty:** Conceptualization, Methodology, Writing – original draft, Review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eti.2023.103017.

References

Abdallah, M., Shanableh, A., Shabib, A., Adghim, M., 2018. Financial feasibility of waste to energy strategies in the United Arab Emirates. Waste Manage. 82, 207–219. http://dx.doi.org/10.1016/j.wasman.2018.10.029.

Akinshilo, A.T., Olofinkua, J.O., Olamide, O., Asuelinmen, E.A., 2019. Energy potential from municipal solid waste (MSW) for a developing metropolis. J. Therm. Eng. 5, 196–204. http://dx.doi.org/10.18186/thermal.654322.

Annual Report 2020-21 on Implementation of Solid Waste Management Rules, 2016, https://cpcb.nic.in/uploads/MSW/MSW_AnnualReport_2020-21.pdf.

Belgiorno, V., de Feo, G., della Rocca, C., Napoli, R.M.A., 2003. Energy from gasification of solid wastes. Waste Manage. 23, 1–15. http://dx.doi.org/10.1016/S0956-053X(02)00149-6.

Beyene, H.D., Werkneh, A.A., Ambaye, T.G., 2018. Current updates on waste to energy (WtE) technologies: a review. Renew. Energy Focus 24, 1–11. http://dx.doi.org/10.1016/j.ref.2017.11.001.

Bhawan, P., Nagar, A., 2022. FORM v [see rule 24(3)] Annual Report in respect of NCT of Delhi for the Central Pollution Control Board.

Bosmans, A., Vanderreydt, I., Geysen, D., Helsen, L., 2013. The crucial role of waste-to-energy technologies in enhanced landfill mining: a technology review. J. Clean Prod. 55, 10–23. http://dx.doi.org/10.1016/j.jclepro.2012.05.032.

Brereton, C., 1996. Municipal solid waste — incineration, air pollution control and ash management. Resour. Conserv. Recycl. 16, 227–264. http://dx.doi.org/10.1016/0921-3449(95)00059-3.

Brunner, P.H., Rechberger, H., 2015. Waste to energy – key element for sustainable waste management. Waste Manage. 37, 3–12. http://dx.doi.org/10.1016/j.wasman.2014.02.003.

Chaliki, P., Psomopoulos, C., Themelis, N., 2016. WTE plants installed in European cities: a review of success stories. Manage. Environ. Qual. Int. J. 27, 606–620. http://dx.doi.org/10.1108/MEQ-01-2015-0018.

Chen, Y., Rözler, B., Zielonka, S., Lemmer, A., Wonneberger, A.-M., Jungbluth, T., 2014. The pressure effects on two-phase anaerobic digestion. Appl. Energy 116, 409–415. http://dx.doi.org/10.1016/j.apenergy.2013.11.012.

Cheng, H., Hu, Y., 2010. Municipal solid waste (MSW) as a renewable source of energy: Current and future practices in China. Bioresour. Technol. 101, 3816–3824. http://dx.doi.org/10.1016/j.biortech.2010.01.040.

Chinwan, D., Pant, S., 2014. Waste to Energy in India and its Management. Number 1, 89–94.

Cimpan, C., Wenzel, H., 2013. Energy implications of mechanical and mechanical–biological treatment compared to direct waste-to-energy. Waste Manage. 33, 1648–1658. http://dx.doi.org/10.1016/j.wasman.2013.03.026.

Cole-Hunter, T., Johnston, F.H., Marks, G.B., Morawska, L., Morgan, G.G., Overs, M., Porta-Cubas, A., Cowie, C.T., 2020. The health impacts of waste-to-energy emissions: a systematic review of the literature. Environ. Res. Lett. 15, 123006. http://dx.doi.org/10.1088/1748-9326/abae9f.

Commission, E., Energy, D.-G. for, 2022. EU Energy in Figures: Statistical Pocketbook 2022. Publications Office of the European Union, http://dx.doi.org/10.2833/334050.

Consonni, S., Giugliano, M., Grosso, M., 2005. Alternative strategies for energy recovery from municipal solid waste: Part B: Emission and cost estimates. Waste Manage. 25, 137–148. http://dx.doi.org/10.1016/j.wasman.2004.09.006.

Cortés, C., Gil, A., 2007. Modeling the gas and particle flow inside cyclone separators. Prog. Energy Combust. Sci. 33, 409–452. http://dx.doi.org/10.1016/j.pecs.2007.02.001.

2022. Criteria Air Pollutants, US EPA Website. https://www.epa.gov/criteria-air-pollutants.

Cucchiella, F., D'Adamo, I., Gastaldi, M., 2014. Sustainable management of waste-to-energy facilities. Renew. Sustain. Energy Rev. 33, 719–728. http://dx.doi.org/10.1016/j.rser.2014.02.015.

Curry, N., Pillay, P., 2012. Biogas prediction and design of a food waste to energy system for the urban environment. Renew. Energy 41, 200–209. http://dx.doi.org/10.1016/j.renene.2011.10.019.

Demaria, F., Schindler, S., 2016. Contesting urban metabolism: Struggles over waste-to-energy in Delhi, India. Antipode 48, 293–313. http://dx.doi.org/10.1111/anti.12191.

Dong, J., Tang, Y., Nzihou, A., Chi, Y., Weiss-Hortala, E., Ni, M., Zhou, Z., 2018. Comparison of waste-to-energy technologies of gasification and incineration using life cycle assessment: Case studies in Finland, France and China. J. Clean Prod. 203, 287–300. http://dx.doi.org/10.1016/j.jclepro.2018.08.139.

Duran, J.Z., Caldona, E.B., 2020. Design of an activated carbon equipped-cyclone separator and its performance on particulate matter removal. Particul. Sci. Technol. 38, 694–702. http://dx.doi.org/10.1080/02726351.2019.1607637.

Eddine, B.T., Salah, M.M., 2012. Solid waste as renewable source of energy: current and future possibility in Algeria. Int. J. Energy Environ. Eng. 3, 17. http://dx.doi.org/10.1186/2251-6832-3-17.

Evangelisti, S., Tagliaferri, C., Clift, R., Lettieri, P., Taylor, R., Chapman, C., 2015. Life cycle assessment of conventional and two-stage advanced energy-from-waste technologies for municipal solid waste treatment. J. Clean Prod. 100, 212–223. http://dx.doi.org/10.1016/j.jclepro.2015.03.062.

Fadillah, G., Fatimah, I., Sahroni, I., Musawwa, M.M., Mahlia, T.M.I., Muraza, O., 2021. Recent progress in low-cost catalysts for pyrolysis of plastic waste to fuels. Catalysts 11 (837), http://dx.doi.org/10.3390/catal11070837.

Fruergaard, T., Astrup, T., 2011. Optimal utilization of waste-to-energy in an LCA perspective. Waste Manage. 31, 572–582. http://dx.doi.org/10.1016/j.wasman.2010.09.009.

Galanakis, C.M., Kordulis, C., Kanellaki, M., Koutinas, A.A., Bekatorou, A., Lycourghiotis, A., 2012. Effect of pressure and temperature on alcoholic fermentation by *Saccharomyces cerevisiae* immobilized on γ-alumina pellets. Bioresour. Technol. 114, 492–498. http://dx.doi.org/10.1016/j.biortech.2012.03.010.

Gumisiriza, R., Hawumba, J.F., Okure, M., Hensel, O., 2017. Biomass waste-to-energy valorisation technologies: a review case for banana processing in uganda. Biotechnol. Biofuels 10, 11. http://dx.doi.org/10.1186/s13068-016-0689-5.

Hamad, T.A., Agll, A.A., Hamad, Y.M., Sheffield, J.W., 2014. Solid waste as renewable source of energy: current and future possibility in Libya. Case Stud. Therm. Eng. 4, 144–152. http://dx.doi.org/10.1016/j.csite.2014.09.004.

Helsen, L., Bosmans, A., 2010. Waste-to-energy through thermochemical processes: matching waste with process.

Hettenhaus, J.R., 1998. Ethanol fermentation strains present and future requirements for biomass to ethanol commercialization.

Hilkiah Igoni, A., Ayotamuno, M.J., Eze, C.L., Ogaji, S.O.T., Probert, S.D., 2008. Designs of anaerobic digesters for producing biogas from municipal solid-waste. Appl. Energy 85, 430–438. http://dx.doi.org/10.1016/j.apenergy.2007.07.013.

Hu, Y., Cheng, H., Tao, S., 2018. The growing importance of waste-to-energy (WTE) incineration in China's anthropogenic mercury emissions: Emission inventories and reduction strategies. Renew. Sustain. Energy Rev. 97, 119–137. http://dx.doi.org/10.1016/j.rser.2018.08.026.

Huang, H., Qureshi, N., Chen, M.-H., Liu, W., Singh, V., 2015. Ethanol production from food waste at high solids content with vacuum recovery technology. J. Agric. Food Chem. 63, 2760–2766. http://dx.doi.org/10.1021/jf5054029.

Ionescu, G., Rada, E.C., Ragazzi, M., Mărculescu, C., Badea, A., Apostol, T., 2013. Integrated municipal solid waste scenario model using advanced pretreatment and waste to energy processes. Energy Convers. Manage. 76, 1083–1092. http://dx.doi.org/10.1016/j.enconman.2013.08.049.

Joseph, A.M., Snellings, R., Heede, P., Matthys, S., de Belie, N., 2018. The use of municipal solid waste incineration ash in various building materials: A belgian point of view. Materials 11, 141. http://dx.doi.org/10.3390/ma11010141.

Kalogo, Y., Habibi, S., MacLean, H.L., Joshi, S.v., 2007. Environmental implications of municipal solid waste-derived ethanol. Environ. Sci. Technol. 41, 35–41. http://dx.doi.org/10.1021/es061117b.

Kalyani, K.A., Pandey, K.K., 2014. Waste to energy status in India: A short review. Renew. Sustain. Energy Rev. http://dx.doi.org/10.1016/j.rser.2013.11.020.

Kamal, M.S., Razzak, S.A., Hossain, M.M., 2016. Catalytic oxidation of volatile organic compounds (VOCs) – A review. Atmos. Environ. 140, 117–134. http://dx.doi.org/10.1016/j.atmosenv.2016.05.031.

Khoo, H.H., 2009. Life cycle impact assessment of various waste conversion technologies. Waste Manage. 29, 1892–1900. http://dx.doi.org/10.1016/j.wasman.2008.12.020.

Koppmann, R., von Czapiewski, K.., Reid, J.S., 2005. A review of biomass burning emissions, part I: gaseous emissions of carbon monoxide, methane, volatile organic compounds, and nitrogen containing compounds. Atmos. Chem. Phys. Discuss. 5, 10455–10516. http://dx.doi.org/10.5194/acpd-5-10455-2005.

Kumar, S., 2000. Technology options for municipal solid waste-to-energy project.

Kumar, S., Smith, S.R., Fowler, G., Velis, C., Kumar, S.J., Arya, S., Rena null Kumar, R., Cheeseman, C., 2022. Challenges and opportunities associated with waste management in India. R. Soc. Open Sci. 4, 160764. http://dx.doi.org/10.1098/rsos.160764.

Lam, C.H.K., Ip, A.W.M., Barford, J.P., McKay, G., 2010. Use of incineration MSW ash: A review. Sustainability http://dx.doi.org/10.3390/su2071943.

2022. Lead poisoning. https://www.who.int/news-room/fact-sheets/detail/lead-poisoning-and-health.

Lewandowski, D.A., 2017. Design of Thermal Oxidation Systems for Volatile Organic Compounds. CRC Press, http://dx.doi.org/10.1201/9781315141060.

Liang, Y., Xu, D., Feng, P., Hao, B., Guo, Y., Wang, S., 2021. Municipal sewage sludge incineration and its air pollution control. J. Clean Prod. 295, 126456. http://dx.doi.org/10.1016/j.jclepro.2021.126456.

Lin, Y., Tanaka, S., 2006. Ethanol fermentation from biomass resources: current state and prospects. Appl. Microbiol. Biotechnol. 69, 627–642. http://dx.doi.org/10.1007/s00253-005-0229-x.

Loganathan, B.G., Masunaga, S., 2009. CHAPTER 18 - PCBs, dioxins, and furans: Human exposure and health effects. In: Gupta, R.C. (Ed.), Handbook of Toxicology of Chemical Warfare Agents. Academic Press, San Diego, pp. 245–253. http://dx.doi.org/10.1016/B978-0-12-374484-5.00018-3.

Lombardi, L., Carnevale, E., Corti, A., 2012. Analysis of energy recovery potential using innovative technologies of waste gasification. Waste Manage. 32, 640–652. http://dx.doi.org/10.1016/j.wasman.2011.07.019.

López, Juan C., Quijano, Guillermo, Souza, Theo S.O., Estrada, José M., Lebrero, Raquel, Muñoz, Raúl, 2013. Biotechnologies for greenhouse gases (CH4, N2O, and CO2) abatement: state of the art and challenges. Appl. Microbiol. Biotechnol. 97, 2277–2303. http://dx.doi.org/10.1007/s00253-013-4734-z.

Ma, W., Wenga, T., Frandsen, F.J., Yan, B., Chen, G., 2020. The fate of chlorine during MSW incineration: Vaporization, transformation, deposition, corrosion and remedies. Prog. Energy Combust. Sci. 76, 100789. http://dx.doi.org/10.1016/j.pecs.2019.100789.

Malav, L.Ch., Yadav, K.K., Gupta, N., Kumar, S., Sharma, G.K., Krishnan, S., Rezania, S., Kamyab, H., Pham, Q.B., Yadav, S., Bhattacharyya, S., Yadav, V.K., Bach, Q.-V., 2020. A review on municipal solid waste as a renewable source for waste-to-energy project in India: Current practices, challenges, and future opportunities. J. Clean Prod. 277, 123227. http://dx.doi.org/10.1016/j.jclepro.2020.123227.

Martinez, D., Ganironm, Jr., T., Taylor, H., 2014. Use of fluidized bed technology in solid waste management. Int. J. U- E-Serv. Sci. Technol. 7, 223–232. http://dx.doi.org/10.14257/ijunesst.2014.7.1.20.

McKay, G., 2002. Dioxin characterisation, formation and minimisation during municipal solid waste (MSW) incineration: review. Chem. Eng. J. 86, 343–368. http://dx.doi.org/10.1016/S1385-8947(01)00228-5.

Ministry of New and Renewable Energy (MNRE), India Website Data extracted from 2020-21 statistics (https://mnre.gov.in/bio-energy/current-status).

Morselli, L., de Robertis, C., Luzi, J., Passarini, F., Vassura, I., 2008. Environmental impacts of waste incineration in a regional system (Emilia Romagna, Italy) evaluated from a life cycle perspective. J. Hazard. Mater. 159, 505–511. http://dx.doi.org/10.1016/j.jhazmat.2008.02.047.

Moya, D., Aldás, C., López, G., Kaparaju, P., 2017. Municipal solid waste as a valuable renewable energy resource: a worldwide opportunity of energy recovery by using Waste-To-Energy Technologies. Energy Procedia 134, 286–295. http://dx.doi.org/10.1016/j.egypro.2017.09.618.

Münster, M., Meibom, P., 2010. Long-term affected energy production of waste to energy technologies identified by use of energy system analysis. Waste Manage. 30, 2510–2519. http://dx.doi.org/10.1016/j.wasman.2010.04.015.

Münster, M., Meibom, P., 2011. Optimization of use of waste in the future energy system. Energy 36, 1612–1622. http://dx.doi.org/10.1016/j.energy.2010.12.070.

Nandan, A., Yadav, B.P., Bose, D., Baksi, S., 2017. Recent scenario of solid waste management in India. World Sci. News 66, 56–74.

Naveen, B.P., Sivapullaiah, P.v., 2020. Solid waste management: Current scenario and challenges in bengaluru. In: Taşeli, B.K. (Ed.), Sustainable Sewage Sludge Management and Resource Efficiency. IntechOpen, Rijeka, http://dx.doi.org/10.5772/intechopen.90837, (Chapter 4).

Nikolausz, M., Kretzschmar, J., 2020. Anaerobic digestion in the 21st century. Bioengineering 7, 157. http://dx.doi.org/10.3390/bioengineering7040157.

Nixon, J.D., Dey, P.K., Ghosh, S.K., 2017. Energy recovery from waste in India: An evidence-based analysis. Sustain. Energy Technol. Assess. 21, 23–32. http://dx.doi.org/10.1016/j.seta.2017.04.003.

Nizami, A., Rehan, M., Ouda, O.K.M., Shahzad, K., Sadef, Y., Iqbal, T., Ismail, I.M.I., 2015. An argument for developing waste-to-energy technologies in Saudi Arabia. Chem. Eng. Trans. 45, 337–342. http://dx.doi.org/10.3303/CET1545057.

Ouda, O.K.M., Raza, S.A., Nizami, A.S., Rehan, M., Al-Waked, R., Korres, N.E., 2016. Waste to energy potential: A case study of Saudi Arabia. Renew. Sustain. Energy Rev. 61, 328–340. http://dx.doi.org/10.1016/j.rser.2016.04.005.

Pak, S.I., Chang, K.S., 2006. Performance estimation of a venturi scrubber using a computational model for capturing dust particles with liquid spray. J. Hazard. Mater. 138, 560–573. http://dx.doi.org/10.1016/j.jhazmat.2006.05.105.

Pandey, B.K., Vyas, S., Pandey, M., Gaur, A., 2016. Municipal solid waste to energy conversion methodology as physical, thermal, and biological methods. Curr. Sci. Perspect. 2, 39–46.

Paolini, V., Petracchini, F., Segreto, M., Tomassetti, L., Naja, N., Cecinato, A., 2018. Environmental impact of biogas: A short review of current knowledge. J. Environ. Sci. Health A 53, 899–906. http://dx.doi.org/10.1080/10934529.2018.1459076.

Pařízek, T., Bébar, L., Stehlík, P., 2008. Persistent pollutants emission abatement in waste-to-energy systems. Clean Technol. Environ. Policy 10, 147–153. http://dx.doi.org/10.1007/s10098-007-0135-2.

Pawlak-Kruczek, H., Niedzwiecki, L., Sieradzka, M., Mlonka-Mędrala, A., Baranowski, M., Serafin-Tkaczuk, M., Magdziarz, A., 2020. Hydrothermal carbonization of agricultural and municipal solid waste digestates – Structure and energetic properties of the solid products. Fuel 275, 117837. http://dx.doi.org/10.1016/j.fuel.2020.117837.

Persson, U., Münster, M., 2016. Current and future prospects for heat recovery from waste in European district heating systems: A literature and data review. Energy 110, 116–128. http://dx.doi.org/10.1016/j.energy.2015.12.074.

Phillips, J., 2006. Different types of gasifiers and their integration with gas turbines. p. 11.

Quina, M.J., Bordado, J.C.M., Quinta-Ferreira, R.M., 2011. Air pollution control in municipal solid waste incinerators. In: Khallaf, M.K. (Ed.), The Impact of Air Pollution on Health, Economy, Environment and Agricultural Sources. IntechOpen, Rijeka, http://dx.doi.org/10.5772/17650, (Chapter 16).

Ranjith Kharvel Annepu Advisor, by, Themelis Stanley-Thompson Professor Emeritus, N.J., 2012. Sustainable solid waste management in India.

Rao, P.V., Baral, S.S., Dey, R., Mutnuri, S., 2010. Biogas generation potential by anaerobic digestion for sustainable energy development in India. Renew. Sustain. Energy Rev. 14, 2086–2094. http://dx.doi.org/10.1016/j.rser.2010.03.031.

2014. Report of the task force on waste to energy (volume i) (in the context of integrated MSW management) planning commission submission certificate of the report of the task force. i Preface ii Acknowledgements v.

Ruokojärvi, P.H., Asikainen, A.H., Tuppurainen, K.A., Ruuskanen, J., 2004. Chemical inhibition of PCDD/F formation in incineration processes. Sci. Total Environ. 325, 83–94. http://dx.doi.org/10.1016/j.scitotenv.2003.11.006.

Rushton, L., 2003. Health hazards and waste management. Br. Med. Bull. 68, 183–197. http://dx.doi.org/10.1093/bmb/ldg034.

Sadiq, M., Kaneesamkandi, Z., 2013. Biodegradable waste to biogas: Renewable energy option for the Kingdom of Saudi Arabia. Int. J. Innov. Appl. Stud. 4, 101–113.

Schneider, D., Lonèar, D., Bogdan, Z., 2010. Cost analysis of waste-to-energy plant 52, 369–378.

Shimizu, T., Toyono, M., Ohsawa, H., 2007. Emissions of NOx and N2O during co-combustion of dried sewage sludge with coal in a bubbling fluidized bed combustor. Fuel 86, 957–964. http://dx.doi.org/10.1016/j.fuel.2006.10.001.

Singh, R.P., Tyagi, V.v., Allen, T., Ibrahim, M.H., Kothari, R., 2011. An overview for exploring the possibilities of energy generation from municipal solid waste (MSW) in Indian scenario. Renew. Sustain. Energy Rev. http://dx.doi.org/10.1016/j.rser.2011.07.071.

Skaggs, R.L., Coleman, A.M., Seiple, T.E., Milbrandt, A.R., 2018. Waste-to-energy biofuel production potential for selected feedstocks in the conterminous United States. Renew. Sustain. Energy Rev. 82, 2640–2651. http://dx.doi.org/10.1016/j.rser.2017.09.107.

Tan, S.T., Hashim, H., Lim, J.S., Ho, W.S., Lee, C.T., Yan, J., 2014. Energy and emissions benefits of renewable energy derived from municipal solid waste: Analysis of a low carbon scenario in Malaysia. Appl. Energy 136, 797–804. http://dx.doi.org/10.1016/j.apenergy.2014.06.003.

Vehlow, J., 2015. Air pollution control systems in WtE units: An overview. Waste Manage. 37, 58–74. http://dx.doi.org/10.1016/j.wasman.2014.05.025.

Wang, Y., Geng, S., Zhao, P., Du, H., He, Y., Crittenden, J., 2016. Cost–benefit analysis of GHG emission reduction in waste to energy projects of China under clean development mechanism. Resour. Conserv. Recycl. 109, 90–95. http://dx.doi.org/10.1016/j.resconrec.2016.02.010.

Wang, Y., Yan, Y., Chen, G., Zuo, J., Yan, B., Yin, P., 2017. Effectiveness of waste-to-energy approaches in China: from the perspective of greenhouse gas emission reduction. J. Clean Prod. 163, 99–105. http://dx.doi.org/10.1016/j.jclepro.2015.09.060.

Wei, J., Li, H., Liu, J., 2021. Fate of dioxins in a municipal solid waste incinerator with state-of-the-art air pollution control devices in China. Environ. Pollut. 289, 117798. http://dx.doi.org/10.1016/j.envpol.2021.117798.

World, T., Washington, B., 1999. Municipal solid waste incineration.

Xu, Y., Liu, X., Zhang, Y., Sun, W., Zhou, Z., Xu, M., Pan, S., Gao, X., 2016. Field measurements on the emission and removal of PM2.5 from coal-fired power stations: 3, Direct comparison on the PM removal efficiency of electrostatic precipitators and fabric filters. Energy Fuels 30, 5930–5936. http://dx.doi.org/10.1021/acs.energyfuels.6b00425.

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

Yen, Hong-Wei, Ho, Shih-Hsin, Chen, Chun-Yen, Chang, Jo-Shu, 2015. CO_2, NO_x and SO_x removal from flue gas via microalgae cultivation: A critical review. Biotechnol. J. 10, 829–839. http://dx.doi.org/10.1002/biot.201400707.

Zaman, A., 2013. Life cycle environmental assessment of municipal solid waste to energy technologies. Int. J. Environ. Res. 3, 155–163.

Zaman, C.Z., Pal, K., Yehye, W.A., Suresh Sagadevan, S.T., Adebisi, G.A., Emy Marliana, R.F., Johan, 2017. Pyrolysis: A sustainable way to generate energy from waste. In: Samer, M. (Ed.), Pyrolysis. IntechOpen, Rijeka, http://dx.doi.org/10.5772/intechopen.69036, (Chapter 1).

Zazouli, M.A., Yousefi, Z., 2008. Removal of heavy metals from solid wastes leachates coagulation-flocculation process. J. Appl. Sci. 8, 2142–2147. http://dx.doi.org/10.3923/JAS.2008.2142.2147.