Applied Chemical Engineering (2024) Volume 7 Issue 4 ISSN: 2578-2010 (O)
doi: 10.59429/ace.v7i4.5578

REVIEW ARTICLE

A comprehensive review of waste-to-energy technologies: Pathways for large scale applications

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ABSTRACT

Waste to energy (WtE) is a strategic tool to address the waste management and stupendous energy demand in a country like India. This paper provides a broad examination of the technological, and economical aspects of WtE projects internationally and specifically in India. Technologically it discusses various WtE processes such as but not limited to gasification, anaerobic digestion and incineration and their suitability as well as capability of handling different types of waste. The study draws attention to the technology that makes these processes more feasible and sustainable in urban and rural areas. From an environmental stand point, the study evaluates the enormous roles played by WtE including; elimination of landfill use, reduction of greenhouse gas emissions and appropriate disposal of solid wastes. It considers the environmental swapping and outlines how WtE can meet India's Sustainable Development Goals, more specifically Sustainable Development Goals 7, 11 and 13: Affordable and Clean Energy, Sustainable Cities and Communities, Climate Action. From the economical perspective, the study performs the cost benefit evaluation, determining economic viability of WtE based projects. The research also provides information about the various factors that contribute to the lack of economic feasibility such as high initial capital investment requirements, operations issues, and government constraints. This study shows WtE projects when implemented they have massive environmental and economic benefits, but the existing infrastructure, good policies and effective stakeholders' engagement determines the success of the projects.

Keywords: Waste to Energy; Waste management; Energy demand; Sustainable waste management; Economic feasibility

ARTICLE INFO

Received: 3 December 2024
Accepted: 19 December 2024
Available online: 31 December 2024

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1. Introduction

1.1. Introduction to energy demand and management

Energy demand is the total energy that is used to support activities in various categories such as residential, industrial and commercial. Energy demand is critical to growth and development of the economy, conservation of natural resources and supply of services considered crucial for wellbeing [1,2]. Energy is one of the significant propellers of economic activities since international researches have estimated a direct relationship between energy consumption and GDP growth asserting that availability of energy is important for industries, transportation and service sector [3]. This is so especially for the developing economies to which energy is critical in facilitating industrial growth and a better standard of living [3] . That is why energy required for the economic growth is being criticized as it leads to environmental concerns. Therefore, the major cause of unanticipated climate change is hence the reliance on fossil energy [1] . Hence one of the key strategies among domestic measures are demand side management and efforts towards the use of renewable energy sources. Further, availability of energy was also found it may have the potentiality to enhance the standard of living. It can unlock education, healthcare, and technology that are highly important in enhancing the societies' standard [4]. However, energy poverty or the absence of access to modern energy services is likely to slow development and lock in inequities. The measures which are to be frequently considered and practiced are referred to as demand side management DSM plans. They consist of enhancing energy efficiency and changing consumption trends towards energy in order to conserve energy and avoid high environmental impacts [5].

1.2. Challenges in India's waste management and energy demand

There are a number of barriers in the Indian context concerning waste management and energy requirements because of increasing urbanization and population. The population density of the urban areas is growing rapidly and as a result they are producing a large amount of waste, which the waste management sectors cannot handle. repositories also experience inadequate waste collection and segregation whereby waste mostly remains uncollected especially in rural areas. The corresponding level of waste segregation in urban areas means that biodegradable and non-biodegradable waste are collected together, making recycling and disposal more difficult [6] . Though recycling rates are considerably low in India mainly because of absence of well-defined recycling channels and scanty public awareness for the system. As a result, productive organic waste is chucked in the dustbin or better still dumped in the landfill sites instead of recycling through composting. These remain landfills many of which are over filled and improperly operated constitute major sources of environmental effects, different forms of contamination from soil to water and precipitation, and air pollution resulting from open burning of wastes [7] . Poor disposal also affects human health since it breeds disease causing agents like mosquitoes and contaminates water sources. Energy security of the country remains woefully inadequate especially where fossil fuel, principally coal generates electricity. This contradicts the use of renewable resources and escalates pollution and production of greenhouse gases [8] . Even though there are numerous opportunities for development of renewable energy like solar, wind and biomass energy, the techniques for deploying these sources and incorporation in to the conventional energy distribution system remains under development stage requiring large amounts of capital and favorable policies. Generating capacity and access to electricity is still inconsistent across the world especially in the rural areas many of which are still in energy poverty. Moreover, the energy infrastructure, transmission, and distribution network are in most of the cases are weak and unresponsive, thus most of the energy being transmitted is wasted due to high losses and frequent power blackouts [9]. While Indian policies have brought in apparently positive measures for renewal energy and efficiency improvement, these appear weak on implementation and enforcement, thus the need for better policies.

1.3. The relevance and benefits of WtE in India

Waste Collection and energy utilization per capita both are the main focal points in a country like India that can be addressing through the Waste-to-energy (WtE) conversion techniques. Thus, several traditional techniques of disposal of wastes inclusive of open dumping and land filling are unenviable in terms of risks or difficult because of increased urbanization and industrialization. This being said that, WtE technologies, such as incineration, anaerobic digestion, and gasification, provide a solution by taking Municipal solid waste and transforming it into usable energy so as to take the capacity of the waste flow bound for landfills [10] . Furthermore, this approach minimizes the impacts like leachate generation touching the soil and water table, methane emissions into the atmosphere, and efficient management of the increasing waste type [6] . In addition, the prospects offered by WtE conversion are not limited by the solution of the problem of effective waste disposal only. However, from an economic point of view, it will complete the energy portfolio by offering a different type of energy and, therefore, contribute to energy security. Thus, in a country such as India, where the demand for energy is steadily rising, and there is excessive dependence on fossils, WtE can also contribute significantly to addressing energy issues [11] . Interestingly, WtE projects can be a source of income from electricity generation and sales as well as bio-fertilizers resulting from the process of anaerobic digestion which will motivate the participation of both the municipal authorities and private business entities [12]. Having the POTENTIAL to abate waste going to landfills and thus reduce methane, a potent greenhouse gas, a WtE assists with climate change objectives. Furthermore, today's WtE plants also have better air pollution control measures in place to reduce emissions which can be far worse than open burning or landfill fire.

1.4. Global status of WtE

The global status of waste-to-energy (WtE) conversion shows considerable variation in implementation and technology adoption. In the U.S., about 29 million tons of waste are processed annually through incineration and anaerobic digestion, with facilities like Covanta Energy leading the way. The EU processes over 90 million tons, with Germany, France, Italy, and the Netherlands employing incineration, anaerobic digestion, and gasification. China processes 60 million tons, primarily through incineration, while Japan handles over 40 million tons using advanced technologies such as incineration, gasification, and pyrolysis. South Korea processes 10 million tons, and India is expanding its capacity, processing 1.5 million tons annually under initiatives like the Swachh Bharat Mission. Singapore processes 3 million tons through incineration. Globally, incineration leads with 45% of energy generation, followed by anaerobic digestion at 25%, landfill gas recovery at 15%, and emerging technologies like gasification and pyrolysis at 10%. Other methods account for 5%[3,13], as shown in **Figure 1**.

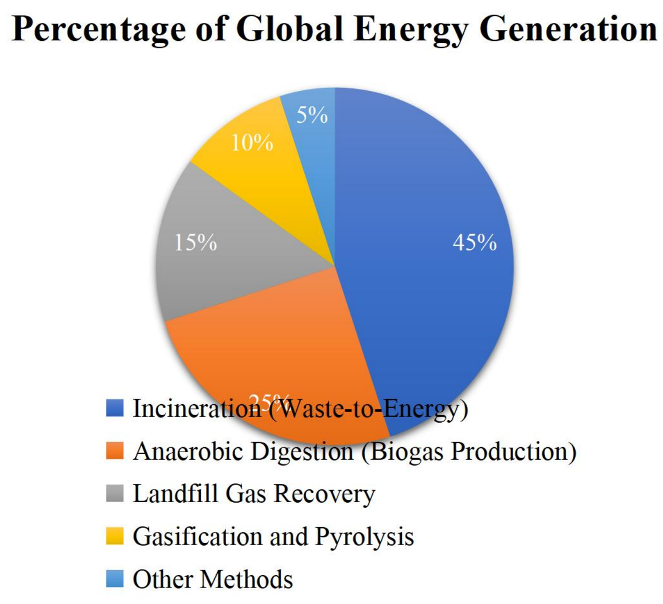


Figure 1. Global trends in waste-to-energy generation across different methods.

1.5. National status of waste to energy

For India, change in waste conversion that is the waste to energy (WtE) conversion is progressive with increased generation of wastes and energy requirements. The nation disposes approximately sixty-two million tons of municipal solid waste annually and management has remained an issue. India has started some project and polities for enhancing WtE like conducting plant like Okhla and Ghazipur in Delhi using incineration technology. As the Swachh Bharat Mission and Smart Cities Mission have sought to augment the waste management structures and encourage WtE. Financial incentives for WtE projects are offered by the Ministry of New and Renewable Energy (MNRE) [12] . However, barriers like high capital cost, heterogeneity of waste and social concern with emissions remain a Bottle neck. Apart from the landfill practice, the OFMS is adopting a number of WtE technologies of which around 40% is based on anaerobic digestion; 30% on incineration; 15% on landfill gas recovery; 10% on RDF and co-processing; and 5% on the technologically advancing gasification and pyrolysis methods. The status of WtE generation in India by these methods is depicted in **Figure 2** [14].

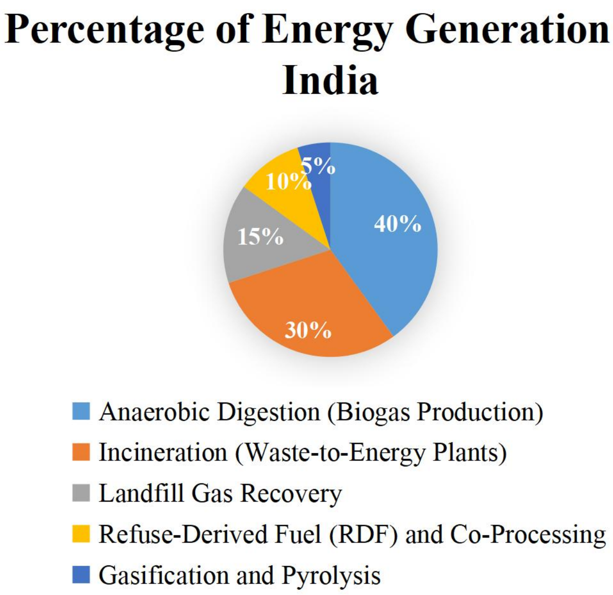


Figure 2. India's waste-to-energy generation by different methods.

The strength of this study derives from the fact that it combines a comprehensive discussion of technological promotion of various WtE processes alongside the analysis of environmental problems and economic viability of each process, with a focus on the Indian environment. It also provides an understanding of their applicability and deployment at small, large, urban and rural scales to help future studies in WtE reflect upon the WtE layout and policies. The paper under the title Moving from 'SuATA' to 'SWaP': Applying Critical Reflection on the 'Energy from Waste' Concept to Empower India focuses on the utilization of waste to energy sources as solutions to the problems of India's Waste Management and the country's energy concerns. And it looked at technological innovation, environmental value addition, economic returns and the current policies and regulations, with indications of gaps. The review also provides the case study of various successful WtE projects and ends with the suggests for the improvement of WtE projects implementation. It also reviews research on Municipal Solid Waste (MSW) management, highlighting challenges from population growth and urban development, and proposes strategies for sustainable waste management. The article is structured into sections on technology, environmental and economic perspectives, challenges, case studies, policy frameworks, and future research directions.

2. Exploring waste to energy technologies

The various WtE technologies that can be deployed in India, including incineration, anaerobic digestion, and gasification. Each technology is evaluated based on its suitability for the Indian context, considering factors such as waste composition, availability of feedstock, and energy output. The advantages and disadvantages of each technology are also discussed, along with case studies of successful implementations in India and other countries. Accordingly, converting municipal solid waste into usable form of energy that mitigates energy generation challenges vis-a-vis waste management covers the domain of waste to energy technologies.

2.1. Technologies related to biological treatments

Biological treatment technologies are essential for converting organic waste into valuable energy resources through natural processes like anaerobic digestion (AD), composting, and fermentation. AD is particularly effective, transforming waste into biogas, saccharides, and organic acids for industrial use. Innovations like psychrophilic and mesophilic biodigesters, powered by renewable energy, enhance biogas production and electricity generation. These methods support energy sustainability and environmental protection. Moreover, effective waste types mainly for AD includes but not limited to, agricultural residues, food waste, industrial organic waste, municipal solid waste, sewage sludge, and dedicated energy crops. AD operates in the absence of oxygen, producing a combustible gas rich in methane and carbon dioxide, with minimum consumption of energy and minimal heat production compared to aerobic processes. The resulting biogas is then used for power and heat generation [15].

2.1.1. Technologies related to anaerobic digestion (AD)

It is an effective means for transforming bio waste into bio energy, solving environmental issues while promoting the materials circularity. It important to state here that this process of producing energy is in effective and sustainable waste management and environmental concerns. As a result, hydrolysis, acidogenesis, acetogenesis and methanogenesis are four major phases of AD process. However, biogas production depends on feedstock composition and on process parameters including temperature, pH and retention time. A stable control of the temperature at mesophilic or thermophilic level and the use of the pre-treatment technologies makes it possible to increase efficiency. Technology in AD is rich since it can accept many types of organic wastes, and can be used to minimize the use of landfill coverage and produce methane in energy form. The final product that is the digestate plays a key role in the bio-fertilizer – driving sustainable agriculture [16].

Anaerobic digestion process

In the acetogenesis phase, VFAs are converted into acetate, hydrogen and carbon dioxide, and these products are assumed to be good electron sources for the anode. The next stage of methanogenesis entails the conversion of acetate and hydrogen into methane as well as carbon dioxide by methanogenic bacteria. AD can be used on any organic matter including agricultural waste, post –harvest residues, human and animals' waste, industrial organic waste and food residuals. The feedstock selection factors include availability of the feedstock, its composition and compatibility with the process of AD. Furthermore, AD has a relatively high potential of providing the following environmental benefits: The avoidance of methane emissions, which is a potent greenhouse gas. In return, AD reduces climate change through collecting methane produced in the digestion process. Besides, it reduces landfilling, and thus lowers the burden of landfill and reduces the generation of both leachate and greenhouse gases [17] . AD also generate biogas, which is another source of energy that does not come from the deposits of oil. Nevertheless, there are challenges associated with the implementation of this technology, including high initial investment costs, together with numerous technical concerns, and feedstock quality issues. More research is needed to improve the overall feasibility of AD systems because the current status of the state of knowledge is just adequate for preliminary investment estimations. Altogether, political support and incentives are also necessary for the wider application of AD for organic waste disposal and for the generation of renewable energy [18].

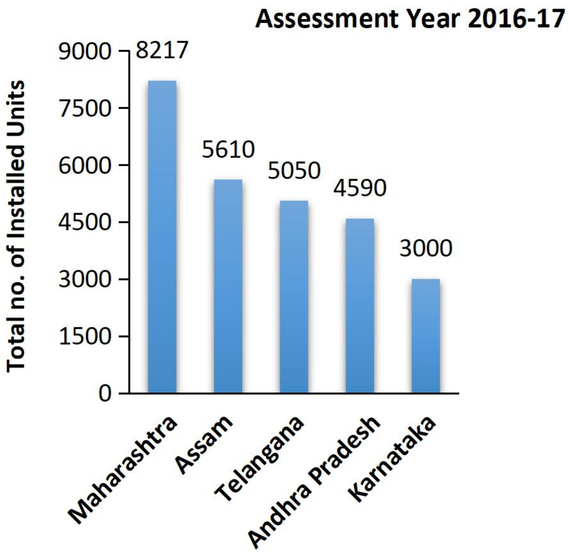
Indian scenario for installation of small-scale anaerobic digestion units

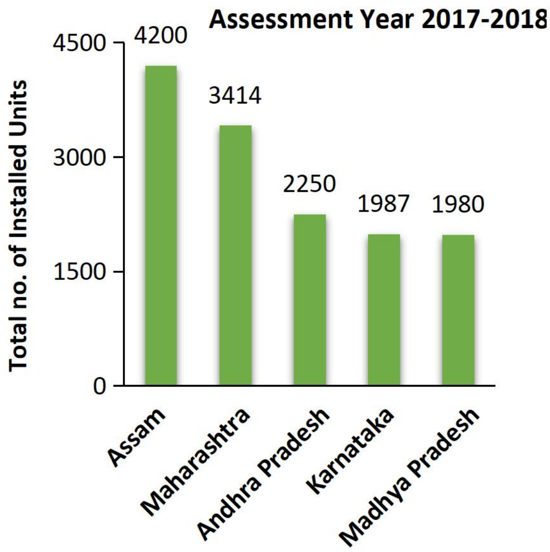
New National Biogas and Organic Manure Programme (NNBOMP) was run during 2016 to 2021 by the Indian government that regularly encourage the anaerobic digestion of several types of biowastes, such as urban biowaste, manure, and crop residues, were financially and technically supported by the Ministry of New and Renewable Energy (MNRE). According to MNRE annual reports, there has been notable growth in small-scale anaerobic digester facilities with small-scale capacities ranging from 1 to 25 cubic meters over the preceding years as summarize in **Table 1**.

Table 1. Year-wise cumulative total of small-scale anaerobic digester units installed in India.

Sr. No.	Assessment Year	Cumulative total number of small-scale anaerobic digester units installed
1.	2016-2017[19]	35557
2.	2017-2018 [20]	55682
3.	2018-2019 [21]	105760
4.	2019-2020 [22]	117779
5.	2020-2021 [12]	138353

Indian state secured top five positions in implementing NNBOMP are shown and state-wise data for total number of installed small-scale anaerobic digestion units in a specific assessment year is represented in **Figure 3**.





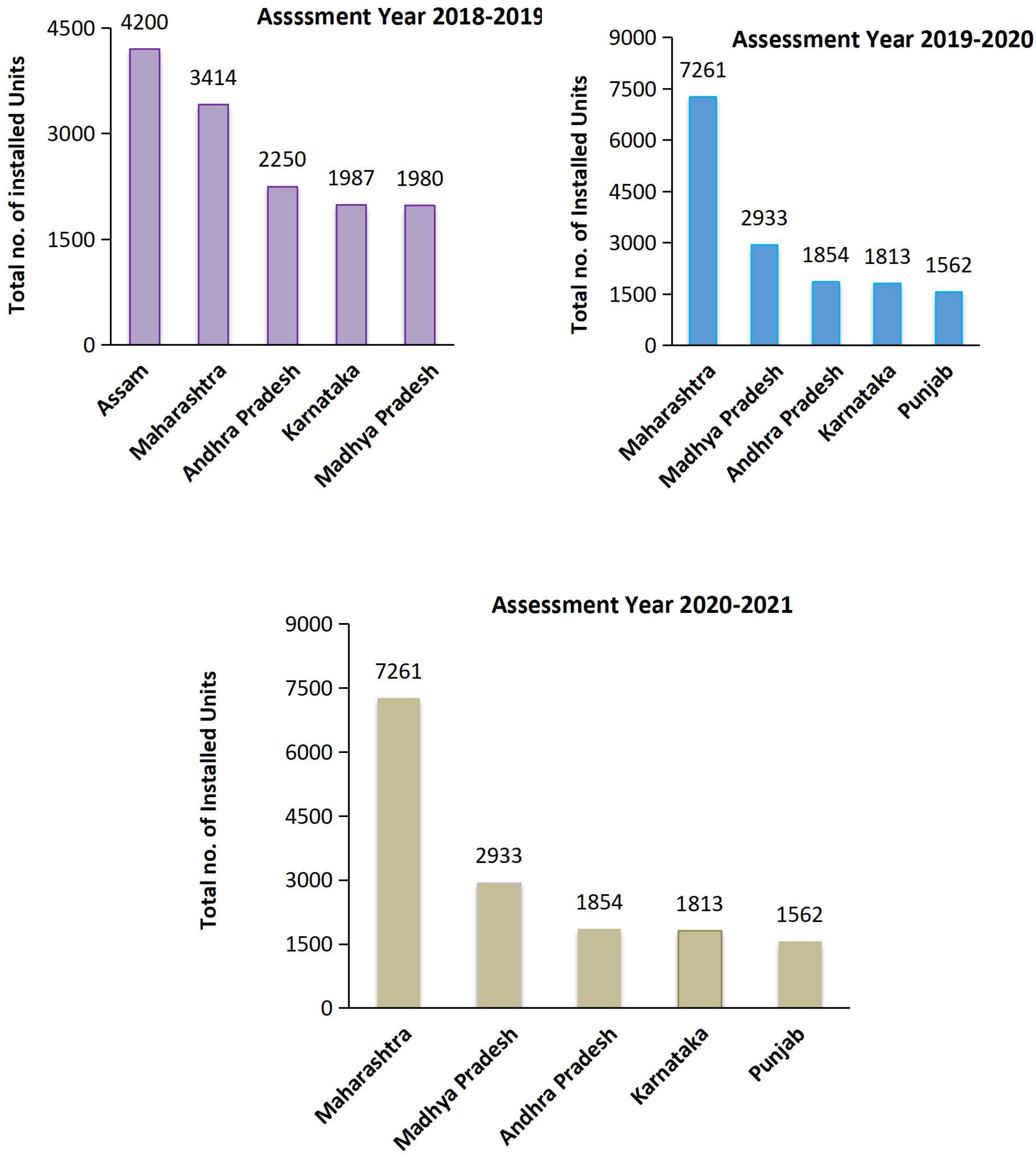


Figure 3. Indian states-wise scenario for installation of small-scale anaerobic digester.

Anaerobic digestion is a valuable technology for treating organic waste and producing renewable energy. It offers several environmental benefits, including methane emissions reduction, waste diversion from landfills, and production of a renewable energy resource. Despite facing challenges, AD has significant potential to contribute to sustainable waste management and renewable energy production.

2.1.2. Composting

Composting is a biological process of stabilizing organic waste through the activities of microorganisms in aerobically designed composting systems so as to improve soil fertility for crop production. The process concerns the microorganisms; initially, mesophilic bacteria function at 25–45°C; later, thermophilic bacteria work at 45–70°C, neutralizing pathogens and weed seeds. High technologies, as well as varieties of additives

Figure 3. (*Continued*)

including livestock manure enhance the degradation of composite components such as cellulose and lignin [23] . Composting not only prevents waste disposal but also adds value to environmental conservation by recycling nutrients and reducing emission of greenhouse gases [24].

2.1.3. Fermentation

Fermentation alters organic matter into additional biofuels, especially ethanol, from biomass including crop wastes. This bioethanol can be mixed with gasoline to help lower levels of greenhouse gases. Advanced fermentation techniques include consolidated fermentation-Microbial fuel cell which combines fermentation and MFC to produce bio-ethanol and bio-electricity from municipal solid wastes and agricultural residues [25]. Dark fermentative technique is also effective for bio-hydrogen production from the municipal solid wastes employing multi-stage processes delivered better performances [26] . Furthermore, the self-generated pre-fermentation of yeast sources and supplementation of biochar can improve the methane production in anaerobic digestion further proving that the advancements of such optimized fermentation technologies can assist waste to energy projects [27].

2.2. Exploring thermal treatment methods as a part of WtE technologies

2.2.1. Incineration

Incineration is a common method for handling solid waste, especially in densely populated urban areas where landfill space is scarce. This process involves burning waste at high temperatures to significantly reduce its volume, recover energy, and lessen its environmental footprint. Modern incineration facilities use advanced technologies for waste handling, combustion, energy recovery, and air pollution control to improve efficiency and reduce emissions[28]. The process of incinerating solid waste is represented in **Figure 4**.

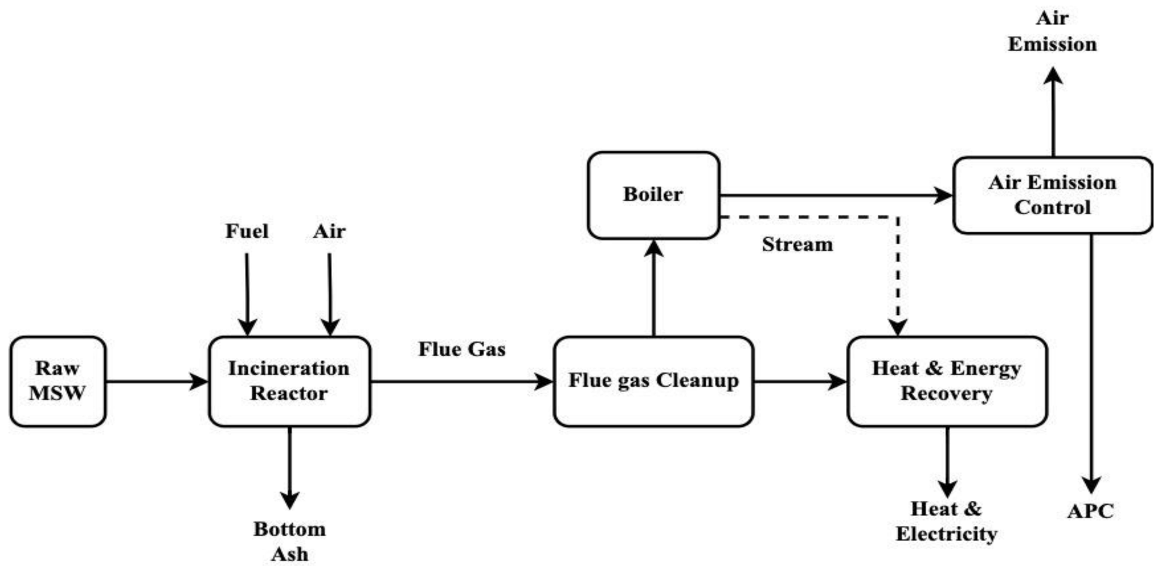


Figure 4. Incineration plant for municipal solid waste (MSW) [29]

Incineration reduces landfill use and methane emissions, and energy recovery can offset fossil fuel use [30]. However, it produces air emissions, including particulate matter and dioxins, which arise health as well as environmental issues. Another important aspect of mayo clinic's waste management is also the safe disposal of ashes which also ought not to pollute the environments [31] . Inclination to incineration has remained high due to continued investment on modernization of its plants to improve service delivery and minimize adverse effects to the environment [32]. New technologies, which are plasma arc gasification and pyrolysis, promise to be better than conventional approaches since they recycle waste and generate useful items without polluting the environment. Sustainable sub-processes, new technologies, and optimization of waste management in terms of volume of wastes to be incinerated are some of the signs indicating that the future of incineration is beginning to look a little more sustainable [33] . Incineration is one of the most widely-used treatment processes for waste which has it own strengths and weaknesses. Though it minimizes the amount of waste and generates energy, it emits some air pollutant emissions, and the ash needs appropriate disposal. To clarify, it is essential for regulating costs and maintaining its sustainability that further investment should keep on being done in the research and development field in order to further optimize production processes and reduce the negative effects on the environment. In addition, actions to minimize waste production and maximization of reuse decreases the tendency of resorting to incineration. Compared to other methods of dealing with waste situation, incineration assist in reducing waste volume, generating energy and minimizing on the use of landfills.

2.2.2. Gasification

Gasification is a thermochemical process whereby carbonaceous feeds are converted through partial oxidation at temperatures greater than 700°C and in an oxygen-limited environment to produce syngas mainly comprising carbon monoxide and hydrogen molecules [34,35]. This process can be divided as Front-end process where first feedstock like coal, biomass, waste or derivatives are selected and second by Operating parameters such as temperature, pressure, gasifying agent etc. Syngas is a multifunctional medium capable of being used for powering electricity-generating gas turbines and engines and as the chemical industry feedstock for generating hydrogen, methanol, ammonia, and synthetic natural gas [35,36] . It can also be converted to liquid fuels including ethanol, diesel and jet and through processes such as Fischer-Tropsch and methanol synthesis. As a mitigation measure, gasification has advantages over conventional combustion involving direct emissions of SO2, NOx, and particulate matter in that it releases some 80% less of these pollutants. It emits some by-products like tar, ammonia and VOCs that causes air pollution and have some effects on the health of the living organisms [37]. However, proper channeling of ash and other byproducts have to be done avoid causing harm to the environment. Finding ways to advance gasification technology, such as CCS can reduce the overall liberal effect caused by this technology. Gasification similarly holds a significant potential in the transformation of carbonaceous materials through clean fuel production with features including high efficiency, and flexibility to other feedstocks. Nevertheless, further investigations are necessary to improve the methods, take full benefit of them and minimize impact on the environment.

Plasma arc gasification (PAG)

Plasma arc gasification is a type of waste treatment technology that employs a plasma arc torch Its efficiency in treating waste is determined by a plasma arc torch that is hotter than 3000°C; waste materials such as organic and inorganic loads are treated through the production of syngas, slag, and metals with a reduction in waste volume and production of energy [38] . It effectively processes the wide range of input including municipal solid waste, biomass, and hazardous material. The process yields syngas that is used for electricity production or for the manufacture of chemicals, and slag, which may be recycled for use in construction, or in the extraction of metals [38] . However, it faces has environmental issues, where there is emission of particulate matter, dioxins besides byproducts that pose future threat to soil and water [39] . The most important and effective method of controlling emissions is required. Plasma arc gasification can cut down the amount of waste sent to landfills and obtain materials and energy thus, it is a viable WtE solution, particularly for areas with limited space for disposal. Further studies are recommended to increase its effectiveness, reduce environmental effects and maximize the benefits arising from its utilization.

2.2.3. Pyrolysis

Pyrolysis is a sophisticated thermochemical process, by which organic waste is converted into reusable energy substrates without the inclusion of oxygen. It also handles non-recyclable waste such as plastics and biomass, and yields bio-fuels, bio-carbon or bio-char, as well as syngas. Pyrolysis produces quality energy materials; gas from municipal plastics and wood blends provide large calorific values 49.45 MJ/m^3. 32 Different biomasses, such as peels and macro algae, enhance bio-oil production showing pyrolysis flexibility. 33 There are three pyrolysis types: slow (300- 500°C, high char), fast (500- 800°C, bio-oil), and flash Product applications vary: In addition to the advantages of biochar increasing the fertility of the soil and acting as carbon storage, bio-oil may be upgraded as a transportation fuel and syngas used in power generation or biofuel manufacture [40] . Despite this pyrolysis has its disadvantage in that it releases volatile organic compounds, as well as biochar having the ability to potentially affect the environment of the soil positively or negatively. The risks associated with external costs can only be prevented through proper system design as well as controlling emissions. Thus, the further study is needed to refine the pyrolysis technology and to reveal the most effective ways to use it for the environmental and economic benefits. The flow diagram presenting the technological process of pyrolysis is attached at **Figure 5**.

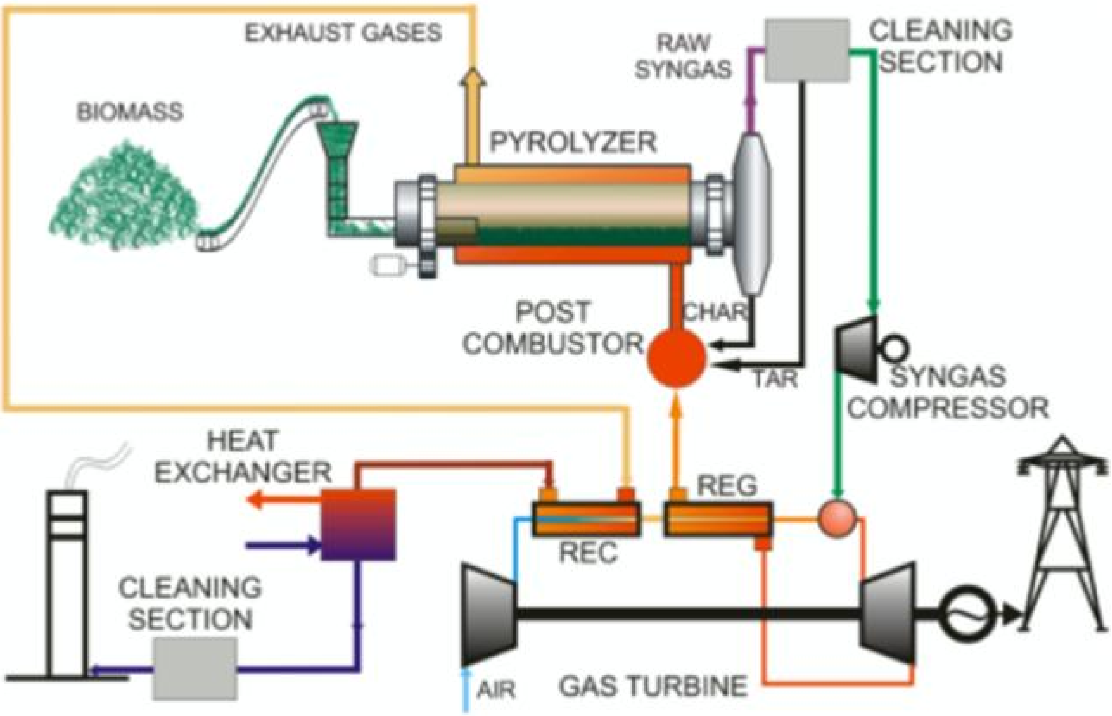


Figure 5. Description of pyrolysis process [35]

2.4. Landfilling gas utilization

The landfilling technique of WtE plays numerous strategies, mechanisms and measures focusing on using energy out of waste with least harm on the environment. A unique method that is used is the cycling of leachate at the landfill, which also raises the output of methane – contributing to the climatization of the landfill thus increasing the output of energy up to 2.2 times more than any other standard ways [42] . Also, landfill gas or mainly methane could be collected and distilled into useful fuels, hence greatly minimizing greenhouse gas emission when used in municipal transport. Furthermore, landfill mining (LFM) is an sustainable solution to extract and reuse underground waste, by energy recovery and in the same time reducing the emissions and getting economic profits. The application of such methods underlines the possible utilization of landfills as the source of energy with considering the environmental problems in focus, especially in those areas with the seasonal fluctuations of wastes production [43]. The various stages showing how landfill gas is used to produce electricity is shown in **Figure 6.** below. Appropriate management of landfill can go along way in decreasing space problems and health complications due to emission of GHG - E.

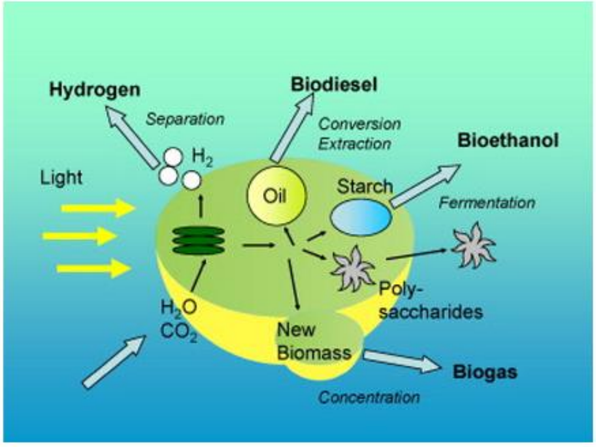


Figure 6. Conversion pathways of microalgae to fuels [44]

2.4.1. Biorefineries: waste-to-by-bioproducts

Waste to bioproducts incorporated in biorefineries hold a lot of potential for the successful achievement of the conversion of waste to energy and overcoming of the environmental challenges. These facilities can turn food wastes, agricultural residues and other organic wastes into bio fuels, bio fertilizers or other valuable chemicals that fits the circular economy column. Coupling of various biorefinery processes improves the overall economic and environmental performances, especially when used in the management and conversion of municipal food waste to energy, it has long-term positive impacts in different areas such as in the US and India [45]. However, problems are still present, for example, the reduction in lipid content in waste in some regions which might restrain efficiency of these systems. In summary, waste biorefineries open up possibilities for renewable energy generation and correspond to several of the SDGs mentioned in this paper: affordable and clean energy and responsible consumption.

2.5. Exploring Bio-fuel technologies

The opportunities in the biofuel technologies for WtE conversion offer a plausible path in the development of sustainable energy. Crop residues; Food Processing Waste; Biomass from agricultural operations thru use of Fermentation, Anaerobic Digestion, Pyrolysis, Gasification, etc can be used to produce biofuels. These technologies do not only increase the sustainability of energy but also decrease the effects of the environment by decreasing greenhouse emissions, managing wastage [46]. Further, MSW has turned out to be more realistic feedstock for biofuel production since new techniques such as nanotechnology improve the conversion rate. Nevertheless, the issues like feedstock variability, logistic complications, and optimal processing conditions are among the factors hindering the large-scale application of biofuels produced from waste materials. Once these obstacles are dealt with by policy support and technological advancements in feed processing, sustainable biofuels from waste will realize their potential, supporting circular economy principles to create a sustainable energy system [47].

2.5.1. Plasma technology

Plasma technology, especially plasma gasification, is rapidly becoming an innovative approach to utilize waste to produce energy. This process involves exposing waste to very high temperatures so that it decomposes the material into its basic components and also forms what is known as synthetic gas or syngas which can be used in generation of electricity or used in chemical processes. It was established that plasma gasification can also be efficient in the treatment of hazardous biomedical wastes – in addition to MSMW –

and what is more, the conversion rate is comparatively high. Moreover, an exergy analysis brings out that plasma gasification is actually feasible and valuable among all other WtE technologies, especially for the proper waste management's challenge in urban areas. Furthermore, plasma treatments are introduced into recycling processes to improve the efficiency of the recycling processes and encourage circular economy concepts [48]. Plasma technology therefore appears to be a viable method for accomplishing waste to energy conversion while effectively balancing the environmental impacts and resource utilization.

2.5.2. Biothanol fermentation

As a technology on bio-ethanol fermentation, it has two unique features; the ability to solve the problems related to management of wastes produced and the manner in which it addresses the problems of energy sustainability. We can bio-convert agricultural residues and food waste through enzymatic hydrolysis and fermentation into bioethanol to also help in the advancement of a circular bioeconomy. Paddy straw and food waste in particular is an acceptable feedstock for bioethanol production because it contains high levels of carbohydrates [49] . The production of the bioethanol may be initiated by pre-treatment to facilitate the release of sugars within the feedstock and enzymatic hydrolysis to convert sophisticated carbohydrates into fermentable sugars. Other influential parameters include pH and temperature and hence call for great consideration. Using the liquid-state and solid-state fermentations, optimal methods of converting a maximum yield of bioethanol are investigated. There are two major benefits of producing bioethanol from waste: environmental as well as economic. Greenhouse gas emissions of bioethanol production are far lower than those of fossil fuels; some processes even report mere 23 g CO_2 eq/MJ of emissions [50]. Also, feedstock contain wastes that are cheaper to acquire making biofuel relatively cheaper to produce thus increasing on its economic viability. However, the generation of bioethanol has its challenges like any other kind of fuel and these include; Technological barriers and financial barriers. Continued research in this area is required for the enhancement of the process and the commercial practicability of the fermentation processes involved in the production of bioethanol signifies its effectiveness in making the disposition of fossil fuels more environmentally sustainable and cost-effective.

3. Environmental perspectives

WTE technologies are fundamental problems in countering the environmental impacts of waste and energy generation especially due to increased population and industrialization. These technologies help in the reduction of the volume of waste and also generate energy in the process of waste disposal WTE plays both roles of waste disposal and energy production [51].Incineration, anaerobic digestion and gasification and pyrolysis are some of the leading WTE technologies that are available, but their efficiency and impact on the environment may differ. Incineration is the most developed answer to the problem, which turns trash into electricity through combustion but might emit poisonous substances if regulated inaptly. These effects are however eradicated in modern incineration plants due to the use of sophisticated emission control systems in the centers.

Gaseous fermentation of organic matter occurs under an anaerobic process, where it forms biogas and digestate can be used as a bio-fertilizer. This process is particularly the best one for the disposal of organic wastes by minimizing methane emission from the landfill Gasification and pyrolysis convert waste into synthesis gas by its thermochemical process it is more efficient in use than normal incineration. Syngas can be utilized for electricity, heat or synthetic fuel synthesis. WTE technologies include incineration, pyrolysis, gasification and anaerobic digestion and are emerging interest in India due to issues of waste disposal in urban centers. Nonetheless, the application of these technologies has some impacts on the environment including emission, ash disposal and externality as represented by greenhouse emissions. But measures should be taken to control emission and ash they produces should also be dealt efficiently so that they do not harm the environment.

3.1. Regulatory framework and technological advancements

India has provided the legal and institutional instruments and set out the regulatory codes and standards to address WtE technology concern. The CPCB also has an emission standards policy while the MoEF & CC has the policy governing hazardous waste disposal. Such factors as better control of combustion efficiency, functioning of emissions reduction technologies will decrease the impact of WtE technologies on the environment. The application of Waste-to-energy (WtE) conversion technologies lie in India's waste management and energy master plan [52]. Thus, it has to be said that environmental issues remain urgent and should be controlled by their authors. It is thus important to plug the gaps through relevant regulations and from enhanced technologies to enable sustainable WtE facilities. Further research and development work are required to enhance the WtE technologies' efficiency and environmental impact in India. Since WtE conversion technologies have environmental impacts, they generate air emissions, ash, water pollution, and Greenhouse gases (GH) emissions. These effects depend on the kind of WtE technology that is applied as well as the measures applied to its operation. Here is an overview of these key impact categories:

3.1.1. Air emissions

Incineration emits particulate matter (PM), sulphur dioxide (SO2), nitrogen oxides (NOx), and dioxins/furans which build up the smog, harms the health of people and environment as a whole.

Pyrolysis and Gasification: These processes also generate emissions, for instance, volatile organic compounds (VOCs) that are known to accord to certain air pollution impact. Anaerobic Digestion: However, AD can also liberate methane – a potent GHG and Hydrogen sulphide H_2 if not well controlled during the process of biogas production.

3.1.2. Ash disposal

Ash acquired from incineration has other heavy metals and pollutants, which can pollute the ground and water sources if handled unsuitably. Proper ways of ash disposal are very important to avoid negative impacts on the environment. Pyrolysis and Gasification: They also produce ash where some of the pollutants are likely to be found. Some of the measures include safe disposal of ash that is important to reduce the effects on environment.

3.1.3. Water pollution

Leachate: Ash produced by WtE facilities can leach pollutants such as heavy metals and organic materials to water hence must be properly collected and disposed.

Cooling Water Discharge: WtE facilities that use water for cooling are an issue of thermal pollution in waters as the water discharged by the plant is warmer.

3.1.4. Greenhouse gas emissions

Incineration: In WtE plants, waste volume is reduced, and fossil fuel is replaced, but burning releases CO2, and methane.

Anaerobic Digestion: Though it captures and utilizes biogas thus eliminating emissions of methane, it nonetheless emits some methane, a potent GHG.

To minimize these environmental effects, WtE facilities can put into use additional measures for instance; advanced emission control systems, proper ash management besides capturing methane from anaerobic digestion. A part of it, monitoring and checking regimes or systems are also important in enforcing environmental laws and policies and hence reducing impacts.

4. Economic feasibility

Waste to Energy conversion costs, returns and feasibility of WTE technologies such as incineration, anaerobic digestion and gasification. This assessment takes into account the initial cost of investment in equipment, array of investment cost, energy production and associated efficiency, and possible returns from the sale of energy and by-products which are fundamental for the development of WtE projects. But one of the most important factors about these projects is their economic feasibility.

4.1. Factors affecting economic feasibility

Capital Costs: The capital costs such as equipment, substructure, and land cost have a huge influence on the economy of WtE projects.

Operational Costs: Other costs which include those expressed during WtE operation include the cost of maintenance, labor as well as the fuel cost also partakes the dotted line in determining a project's economic feasibility.

Revenue Streams: The revenues sources include sales of electricity, revenue from tipping fees, compost, and RDF (Refuse-Derived Fuel) from WtE operations were applied economically in WtE operations.

Government Incentives: Financial support and incentives provided by the government, such as subsidies, tax benefits, and feed-in tariffs, can significantly enhance the economic viability of WtE projects in India.

5. Challenges and barriers

5.1. Technological barriers

WtE technologies for waste management and energy production have their drawbacks that dictate the need to scale up technology further. Currently, incineration, which is one of the most common and recognized WtE technologies, has numerous environmental and economic disadvantages [53] . The process emits such pollutants as dioxins, furans and particulate matter, which are environmentally and health wise, dangerous for the populace. Additionally, the costs of creating incineration plants are high, and thus incurs some economic factors especially to the developing countries. Also, the setting of incineration facilities may often meet with resistance from residents mainly driven by concerns of pollution, and its impact on the people's health. These risks explain why WtE solutions require superior technologies that can parry environmental impacts, reduce costs, and allay public bemusement, thus improving the viability and perception of WtE solutions.

5.1.1. Technological advancements needed

Improvement of emission control, thermal efficiency, and sorting of the waste collection are the key to eliminating the drawbacks of technologies WtE, especially incineration. The means of lowering such emissions include integrating technologies of emission controls including electrostatic precipitators, scrubbers and fabric filters. The following innovations can reduce pollution including dioxins and particulate matter emission that is associated with incineration. Other priority areas include increasing efficiency of energy recovery such as through upgrading of combined heat and power systems (CHP). Through improving these systems, the energy that is derived from waste in incineration plants can be conserved making the process as economically Toronto: Green Living INITIALED efficient as possible. Furthermore, there is a need to advance the pre-treatment and sorting systems in order to only burn the correct waste. By optimizing the choice of waste, these compaction technologies can increase the WtE Operational performance, and, in turn, minimize the emissions of pollutants, enabling the WtE industry to become cleaner and more effective.

5.2. Anaerobic digestion (AD)

AD stands out as one of the most attractive technologies for organic waste and renewable energy generation. But it has few shortcomings that can affect its performance and productivity. One of the top issues facing AD technology is feedstock fluctuation; the rate at which the digestion processes occur is directly proportional to the nature of the organic feedstock. This results in fluctuation of biogas production and some operational challenges during the process. The two major challenges include: The other major challenge is digestate management. Digestate which is the by-product of the AD process is a tricky subject because of the challenges that come with its disposal or utilization. Secondly, some factors such as pH, temperature and inhibitors influence the stability of the AD process and hampers the process efficiency and stabilization. To overcome these limitations, the following are required technological improvements: Improvements in pre-treatment processes – mechanical, thermal or chemical – can obviously increase the input biodegradability for feedstock, hence the yield in biogas production. Studies in smart microbial design and genetic engineering could go a long way in increasing not only the yield, but the robustness of the AD process as well. In addition, new input output technologies could increase nutrient recycling and permit the recovery and utilization of valuable nutrients of the digestate and thereby improve the sustainability of AD systems. Meeting these needs shall be important in the realization of the strengths that comes with using anaerobic digestion as a sustainable solution to waste management and production of renewable energy.

5.3. Gasification and pyrolysis

Gasification and pyrolysis are two highly developed processes that have much potential for waste conversion and energy generation. As for its peculiarities, here it is necessary to note that they have certain disadvantages that protect them from limitless popularity. The processes of synthesis, modification and degradation of these products and equipment are usually relatively expensive which acts as a constraint because these reactions need enhanced apparatus and skilled personnel to execute them efficiently. Furthermore, these two technologies have special feedstock demands, and the input cannot be contaminated and this limits their usefulness in a wide range of waste streams. Technical factors still prevail and these include a number of problems like tar formation issues, ash disposal and reactor design all of which affect the functionality and operationality of such system. Nevertheless, if the said deficiencies are to be surmounted in order to realize the capabilities of both gasification and pyrolysis self-sustaining technologies are crucial. Newer reactor designs have the potential for raising the efficiency and throughput of these processes dramatically and can therefore expand the practicality of their use. The improvement of catalysts and additives is a key to prevent tar synthesis and enhance the quality of the generated syngas, which to increase the efficiency of the systems. Furthermore, the combination of gasification and pyrolysis with renewable energy systems may enhance the adequacy of economic and environmental benefits of integrated waste management systems and energies.

5.4. Landfill gas recovery

Landfill gas recovery is one of the ways of using methane emissions from wastes and is good but has some problems that affect its production. Old designs used for capturing gas gravely result in significant losses of methane, a greenhouse gas that is twenty-five times more effective in causing climate change than carbon dioxide. In addition, the energy content of landfill gas is often lower than in other forms of WtE technologies thus limiting the amount of energy that they can produce. Further, not all the landfills are capable of the gas recovery that is why this technology has minimal general application. To further improve the effectiveness of landfill gas recovery, a number of technological improvements are needed. Applying new technologies into existing gas collection system can increase the level of methane capture, lowering the greenhouse impact while increasing the velocity. Technological improvement in the purification process is also desirable because such developments can boost the quality and feasibility of landfill gas for generation of energy. Thus, opportunities to use landfill gas for various purposes, for example, as a reagent in industry or as a raw material for biofuels, will increase the potential demand for the same and enhance efficiency of extensive gas collection procedures. Meeting these ITS will be critical to achieving the optimal impact of landfill gas recovery and the development of its function in waste treatment and energy generation.

5.5. Plasma arc gasification

Advanced Plasma Technologies plasma arc gasification as one of the wastes to energy (WtE) solutions can benefit and radically transform waste management conditions, but with certain disadvantages. It entails a lot of power and tools which make it difficult to execute and expensive. High fixed and working capital requirements, what escalated costs even higher, makes it economically doubtful. Some of the important technical improvements are reduction of plasma torch energy consumption, efficiency enhancement and recovery of valuable by-product which is crucial for the technology's sustainability and viability. Two major issues of WtE projects in India are: a) the nascent waste generation infrastructure; b) The policy and financial risks in policies and feed-remaining limitations and challenging resources, particularly in cases of small-scale WtE plants. Solving these problems can make WtE technologies to achieve their potential in sustainable waste disposal.

5.6. Strategies to improve economic viability

Efficiency in identification of best technologies for WtE projects, operational efficiency measures for projects, and strong policy framework is crucial in enhancing the economic attractiveness of WtE projects. Appropriate WtE technologies improve feasibility according to the waste and energy demands of the region; increased competency in waste management and energy production improves financial viability. This simplifies environments: These drive investments, lowering risks and are: Policies, regulations and incentives. PPP financing can solve the financial and operating problems, market development by RECs and carbon credits can contribute to viability of solar products. For promoting sustainable and improved WtE solutions for waste management in India, addressing the challenges inherent in infrastructure, policy and financing are imperative.

6. Case studies and real-world applications

Waste-to-Energy (WtE) technologies offer sustainable solutions for waste management and energy recovery, with applications in civil engineering and material recovery. Residues like bottom ash and fly ash can replace natural materials, reducing resource depletion. They substitute Portland cement, improve road durability, and provide structural support in embankments. Ensuring compliance with environmental standards for heavy metal leaching is crucial for safety. Despite their potential, challenges in standardization and public acceptance persist, requiring further research and public education. Detailed case studies are provided globally and nationally in **Tables 2 and 3**.

Table 2. International case studies from diverse research groups.

Sr. No.	Author	Country	Technology used/Study description	Findings
1	E.K. Paleologos et. Al., 2024[54]	UAE	Recycling and Incineration	• Recycling and incineration are regarded as the most practical methods for waste management. • Abu Dhabi and Dubai, the UAE's largest and most densely populated cities, are situated along the coast. • Landfilling is not recommended in these areas because suitable hydrogeological conditions are lacking.
2	K.Shahzad et. Al., 2017 [55]	UAE	Evaluate the potential for biofuel production from the fat and oil components of municipal solid waste (MSW) in Makkah. Assess	• Processing fat fractions from MSW and slaughterhouse waste reduces land resource burdens and generates economic benefits. • By 2050, 940 thousand tons of waste will

Sr. No.	Author	Country	Technology used/Study description	Findings
			both the economic and environmental viability of biofuel generation, including its potential for electricity production and the reduction of greenhouse gas (GHG) emissions.	produce 130 thousand tons of biodiesel, 13 thousand tons of glycerol, and 244 thousand tons of biofuel. • This will save 533 million SAR in landfill fees, 96 million SAR in carbon credits, 569 million SAR from electricity generation, and 303 million SAR from oil and gas conservation. • Net revenue is projected to grow from 611 million SAR in 2014 to 1274 million SAR by 2050.
3	M.R. Barati et. Al., 2017 [56]	Iran	Anaerobic digestion plant	• A comprehensive exergy analysis was conducted on an OFMSW-fed anaerobic digestion plant in Tehran, Iran. • The overall exergetic efficiency of the plant was 72.8%. • Electric power contributed 15.4% to the plant's overall exergy efficiency. • Liquid and solid biofertilizers accounted for 84.6% of the system's efficiency.
4	F.A.M. Lino et. al., 2018 [57]	Brazil	Incineration, bio digestion and recycling	• Incineration and recycling are effective solutions for MSW treatment in Campinas, Brazil. • Electricity was generated for 134,217 homes through this method. • Recycling helped save electricity equivalent to powering 46% of the homes in the city. • Financial aid equivalent to 1,120 minimum national salaries was provided as a result of this process.
5	Y.LV et. al., 2021 [58]	Czech Republic	Anaerobic Digestion (AD)	• Microwave treatment is more effective for MSW prior to anaerobic digestion (AD), but it has limitations due to higher energy consumption and carbon emissions. • Biogas production can be enhanced by +4% to 39.28% through this method. • Chemical and membrane-based post-treatments offer relatively lower energy consumption.
6	K.Weber et. Al., 2020 [59]	Germany	Mechanical Biological Treatment (MBT) and anaerobic digestion (AD)	• Extensive data collection and evaluation were conducted using both literature sources and a survey of waste treatment plant operators. • Waste treatment plants account for approximately 3.7% of Germany's total energy consumption.
7	Y. Ding et. Al., 2021 [60]	China	Land filling, Incineration and Composting	• A comparison between Chinese provinces and developed cities showed that: 52% of MSW in China is landfilled, 45% is incinerated, 3% is composted • China's waste utilization efficiency is significantly lower than in developed countries. • Integrated MSW management and utilization technologies are recommended.
8	Y. Lv et. Al., 2021 [61]	China	Anaerobic co-digestion	• A mass balance analysis was conducted to assess the efficiency of the proposed process in COD removal. • The analysis showed that bioenergy conversion efficiency could be enhanced by 12% to 18%. • This improvement is achieved through the anaerobic co-digestion of food waste with municipal solid waste leachate.
9	B. Dastjerdi et. Al., 2019 [62]	Australia	land filling with energy recovery, incineration and anaerob ic digestion (AD)	• Greenhouse gas emission reduction potential and energy generation potential were calculated and compared for each method. • Combining incineration and anaerobic digestion can: • Extract a significant amount of energy from residual waste • Mitigate greenhouse gas (GHG) emissions.

Table 2. (*Continued*)

Sr. No.	Author	Country	Technology used/Study description	Findings
10	M. Ezzat salem et. Al., 2022 [63]	Egypt	Incineration technology	• In Cairo, MSW management scenarios include: • Mass burning with 50% of organic material excluded • 25% recycling with partial separation of materials • Analysis (2011–2031) showed: • 597 MW net electric power without recycling • 516 MW with 50% organic material excluded • 484 MW with 25% recycling • 359 MW with both 50% organic material excluded and 25% recycling

Table 3. National case studies on municipal solid waste management by different research groups.

Sr. No.	Author	City	Technology used	Findings
1	M. Chakraborty et. Al., 2013 [64]	Delhi	Plasma arc gasification	• Study assessed 5 WTE technologies: biomethanation, incineration, gasification/pyrolysis, RDF, plasma arc gasification. • Focused on MSW at three Delhi landfills: Ghazipur, Bhalswa, and Okhla. • Examined energy generation potential of MSW under ideal conditions. • Used MSW-specific characteristic parameters for computation. • Provides insights into WTE potential for effective landfill management in urban areas.
2	A. Kumar et. Al., 2017 [10]	Review Paper use data of MSW of various cities across the India	Incineration, pyrolysis, gasification, anaerobic digestion, and landfilling with gas recovery	• Landfilling dominates MSWM in developing countries. • Review aids policymakers in understanding current challenges and barriers. • WTE identified as a renewable energy source. • WTE can partially meet energy demand. • Promotes effective municipal solid waste management (MSWM).
3	J.D. Nixon et. al., 2017 [65]	Karimnagar, Andhra Pradesh.	Data were gathered from three case study facilities: an incinerator, a gasification plant, and a co-firing plant that burns waste alongside coal. This data was then analyzed by comparing it with two waste incinerators in Europe.	• Poor source segregation hampers WtE technology implementation in India. • Severe contamination occurs during transport and storage of MSW. • Indian WtE plants have lower capital costs than European incinerators. • Particulate matter emissions in India are 100 times higher than in Europe.
4	A. Dasgupt	Powai, Mumbai.	Anaerobic Digestion	• Acid pre-treatment enhances biogas generation and reduces retention time.

Table 3. (*Continued*)

Sr. No.	Author	City	Technology used	Findings
	a et. Al., 2020 [48]			• HCl pre-treatment yields more biogas than acetic acid. • Optimal pre-treatment: HCl at pH 3, acetic acid at pH 1. • HCl-treated OFMSW achieves 30-day biogas output in 12 days. • HCl pre-treatment is more cost-effective than acetic acid.
5	T.Gross et. Al., 2021 [66]	Six municipalities of State Maharashtra.	Anaerobic Digestion (AD)	• Anaerobic digestion (AD) covered over half of cooking energy needs in two villages. • AD reduced firewood dependency significantly. • In urban areas, AD is crucial for organic fertilizer supply and pollution control. • Decentralized AD is favorable until biowaste segregation is established. • Agricultural studies should focus on digestate vaporization, nutrient efficiency, soil health, and acceptance in India.
6	B. Patel et. Al., 2023 [67]	Ahmedabad City, Gujarat.	Advanced Controlled Combustion	• Organic waste from Pirana Dumping site in Ahmedabad was characterized for key parameters. • 14.9 MW WTE facility replaces 417 tons of coal daily. • Reduces GHG emissions by 300.38 tCO2eq/day through coal replacement. • Avoids 735.24 tCO2eq/day from landfill emissions by processing MSW.
7	Y. Aryan et. Al., 2023 [68]	Dhanbad city, Jharkhand	Landfilling	• Landfilling contributes 67% to overall environmental impacts. • Material recovery facility with 75% plastic sorting significantly reduces impacts. • Composting 80% of food waste further reduces overall impacts. • Electric tippers showed minimal impact reduction currently. • Future 2030 electricity mix boosts benefits of electric tippers. • S5 scenario had the least environmental impacts compared to current practices. • Public participation is crucial for sustainable MSW management.
				•
8	G. Chandrasekran et al., 2023 [69]	Coimbatore, Tamil Nadu.	Co-pyrolysis	• Acid pre-treatment of SR affects co-pyrolysis and alters product yields. • Maximum pyrolysis oil yield (50.5 wt%) achieved with MSW + TSR + HZSM-5. • Maximum gas yield (38.1 wt%) obtained with MSW + SR + HZSM-5.
9	Y. Aryan et. Al., 2023 [70]	Guahati, Assam.	Pyrolysis.	• Pyrolysis products like biochar and syngas are marketable, usable fuels. • MSW-derived char can be used as fertilizer, soil conditioner, and activated carbon.

7. Policy and regulatory framework

Waste-to-energy (WtE) projects in India operate within a multifaceted policy and regulatory framework encompassing various laws, regulations, and government initiatives.

Policy and Regulatory Framework for WtE Projects in India:

7.1. National policies and initiatives

National Bio-Energy Mission: Aims to promote the utilization of biofuels, including biogas and biofuels from municipal solid waste (MSW), to reduce reliance on fossil fuels.

Swachh Bharat Mission: Seeks to achieve universal sanitation coverage and effective waste management across India, including the promotion of WtE projects.

7.2. Electricity regulations

Electricity Act, 2003: Regulates generation, transmission, distribution and trading of electricity in India and allow the sale of electricity produced from WtE business. Renewable Purchase Obligation (RPO): Requires a minimum percentage of electricity demand of India to be met by renewable energy including the WtE projects.

7.3. Environmental regulations

Environment (Protection) Act, 1986: Consists of the legal provisions of environmental management in India particularly on air and water pollution from WtE projects. Environmental Impact Assessment (EIA) Notification, 2006: Imposes the need for environmental impacts for any project including the WtE projects before they are embarked upon to secure environmental clearance.

7.4. Financial incentives and support

Financial Incentives: To support new WtE elaborations, the governments offer utility subsidies, grant monies, and tax credits for the industry. Viability Gap Funding (VGF): Furnishes provided to WtE projects to fill the funding gap between expenses of establishing the plant and operational costs and income. WtE projects have had the backing of a developed policy and regulations framework in India but the following risks have been realized; including poor waste collection and segregation, issues associated with high capital costs, and a low level of public awareness about the WtE business. To overcome these challenges, in future the more focused policies should be laid down to advance the source segregation of wastes, the financing structures for WtE projects, and creating awareness of the benefits of WtE technologies. Continuous activities are required to overcome the issues and enhance the execution of policies and regulations to support WtE projects in India.

8. Challenges and future directions

Several issues inherent in waste-to-energy (WtE) technologies can be seen in the context of the Indian reality: technology identification and decision-making, funding and permitting, and social acceptance. Waste composition variability and operational efficiency are the primary technological issues. There is a key financial challenge of high capital intensity, unpredictability in revenue generation, and difficulty in sourcing for capital. Challenges are; regulations, policies, legalization, environmental and acquisition of land. The social issues arise from misperceptions and entireness from the community, plus the limitation of engaging stakeholders. Possible actions to consider regarding these challenges include promoting technology development, establishing effective financial instruments, simplifying relevant rules and combining them with the usage of favorable contractual provisions, and organizing publicity campaigns. Governments together with industries and civil societies need to come up with the best solutions to ensure that the potential of WtE technologies is realized in conserving the environment and providing for energy demands in India.

9. Conclusion

Waste to energy technologies have become the viable solutions for Waste management in India, energy generation and sustainability. Although there are opportunities in turning waste into useful products such as electricity and biofuels, the barriers include, compatibility of technology, costs, and ineffectiveness of operations. WtE technologies decreases landfill waste and emission but it has given some environmental concerns such as air pollution and water pollution. Diffusing these impacts calls for stringent regulations, and emission standards. Lastly, and probably most fundamentally, economic viability requires endorsement by supportive policies, and, newly emergent, the creative financing. Overall, the change in WtE policy and implementation, and the blend of technology and research need to be continued for the optimum utilization of WtE in India.

Credit authorship contribution statement

Ujvala Cristian: Writing – original draft, Methodology, Validation, **Yashawant P. Bhalerao:** Writing – original draft, Conceptualization, Formal analysis. **Pranav Mehta:** Writing – review & editing, Resources, **Jaymin Patel:** Writing – Original draft, review & editing, Visualization, Supervision. **Ghanshyam G Tejani:** Writing – Original draft, review & editing **Subhav Singh:** Writing – Original draft, review & editing **Deekshant Varshney:** Writing – Original draft, review & editing

Funding sources

This work did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgment

The authors and co-authors would like to express their gratitude to their institute for providing all the facilities, digital journals, library access, cooperation, and support during the writing of this review.

Conflict of interest

The authors have no conflicts of interest to declare that are directly relevant to the content of this manuscript.

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