



Recent advancements in waste to energy production

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Abstract

This review explores the evolving landscape of waste-to-energy (WtE) technologies as sustainable solutions to the dual challenges of rising energy demands and growing waste generation. It provides a comparative analysis of thermal, biochemical, and physicochemical WtE conversion methods, including incineration, gasification, pyrolysis, anaerobic digestion, fermentation, and trans-esterification. The study highlights the environmental and economic advantages of each process, while also addressing the technological advancements that have enhanced energy recovery efficiency and emission control. Special attention is given to emerging techniques like microbial fuel cells and electrolysis cells, which present promising pathways for future bio-hydrogen production. It also emphasizes the importance of integrating WtE systems into broader waste management strategies aligned with sustainable development goals and the circular economy.

Keywords: Waste-to-energy, sustainable energy, municipal solid waste, thermal conversion, circular economy

Introduction

Air pollution, water pollution, excessive soil erosion and its contamination by various chemicals, the ozone layer depletion, represent a few of the side effects associated with human civilization and industrial growth. The generation of garbage is a noteworthy adverse impact that is also continuously rising. Waste management presents a growing number of challenging issues as civilizations develop and become more urbanized. Conventional waste disposal techniques, such as incineration and landfilling, have long been the go-to strategies for handling the steadily rising amount of industrial and municipal trash. These techniques, however, can have high financial and environmental implications. Within this framework, the idea of waste-to-energy (WtE) production has surfaced as a creative and novel way to deal with the two problems of producing energy and disposing of garbage [1]. The process of turning non-recyclable waste materials into useful energy, usually in the form of heat or electricity, is known as waste-to-energy production. By using this method, the amount of garbage that would otherwise wind up in landfills is decreased, and the waste's potential for energy is also realized. WtE technologies provide a sustainable substitute for traditional waste management techniques and aid in the diversification of energy sources by turning trash into a profitable resource [2].

Waste-to-energy is not a wholly novel idea. From ancient civilizations that burnt rubbish to provide heat to the earliest industrial operations that made use of waste materials, waste has historically been employed as a fuel source in many different cultures. However, improvements in engineering, environmental science, and waste management techniques have led to a considerable evolution in current waste-to-energy technology. Incineration is one of the main processes used in waste-to-energy generation. It entails burning waste materials at high temperatures. Waste is efficiently reduced in volume by this process, which turns it into ash, gases, and heat. Incineration heat may be converted into steam, which powers turbines to provide energy. Advanced emission control systems are installed in modern incinerator plants to reduce air pollution and guarantee an ecologically friendly and efficient burning process [3].

Anaerobic digestion, a biological process that breaks down organic waste in the absence of oxygen, is another important waste-to-energy technique. Anaerobic digestion is the process by which microorganisms break down organic materials to produce biogas, which is a carbon dioxide and methane combination. It is possible to collect the biogas and utilize it as fuel to produce heat or power. Digestate, a nutrient-rich byproduct of digestion that may be added to soil, is another result of digestion. Other cutting-edge waste-to-energy methods that have drawn interest recently are gasification and pyrolysis. Gasification is the process of partially oxidizing waste materials at high temperatures to create synthesis gas, or syngas, which may then be used to make chemicals, fuels, or power. In contrast, pyrolysis is the process of thermally breaking down waste materials without the presence of oxygen in order to create solid, gaseous, and liquid products. One benefit of both gasification and pyrolysis is that they both reduce the amount of leftover garbage while transforming waste into useful goods [4].

The way waste-to-energy technologies are applied across the world differs depending on governmental frameworks, technical development, and the characteristics of the trash in each location. Modern WtE facilities are now a crucial part of waste management plans in many industrialized nations, increasing energy supply and decreasing reliance on landfills. On the other hand, the implementation of WtE technology encounters obstacles in developing regions concerning infrastructure, investment, and regulatory backing. However, there is a great deal of room for improvement in waste management and energy availability with WtE. Waste-to-energy initiatives are developed and implemented with economic concerns in mind. WtE facilities might require a significant capital expenditure that covers building, technology, and operating expenses. Nonetheless, the advantages of energy production, trash diversion, and decreased landfill usage frequently exceed the upfront costs. WtE initiatives may also boost the local economy, provide jobs locally, and improve energy security. A further important component of the waste-to-energy equation is the environmental effects. While waste-to-energy (WtE) technologies have many positive

environmental effects, including lower greenhouse gas emissions and landfill usage, they can also have drawbacks. The energy efficiency of the systems, residue management, and emissions from combustion operations are important aspects that must be carefully taken into account. Strict regulatory frameworks and technological advancements are necessary to mitigate these effects and guarantee the long-term viability of WtE operations [5].

Discussions about waste-to-energy production must also take social issues and public acceptance into account. Gaining support and guaranteeing the effective integration of WtE facilities requires community participation, openness, and resolving local concerns. Education campaigns that dispel myths and emphasize the advantages of WtE can help the public see things more clearly and with more support. To summarise, waste-to-energy production offers a flexible and diverse approach to addressing several urgent issues related to waste management and energy sustainability. Waste-to-energy (WtE) systems reduce landfill usage, provide renewable energy, and mitigate environmental concerns by turning waste materials into valuable energy resources. Waste-to-energy generation is expected to become more and more important in the energy sector as technology develops and the need for sustainability grows globally. One of the EU's most developed sectors is the waste industry. There are national law and secondary law regulations pertaining to the garbage business in the European Union. It prioritizes preventing the generation of trash. If that isn't feasible, an attempt should be made to repurpose them for the same or a different goal. Only after achieving maximum recycling should disposal (treatment) be allowed, if even this is not possible. Energy use ought to be prioritized above landfilling. The European Community also considers efforts to reduce landfilling [6].

when recycling and reuse is not possible, one of the best solutions is thermal treatment combined with heat recovery, and not just in the EU. It offers several benefits over other processes, including: (i) quick treatment times; (ii) the ability to handle hazardous or severely dangerous waste; (iii) the ability to manage off-gas; and (iv) the potential to make meaningful use of the heat produced during the oxidation process. Environmental regulation continuously raises the byproduct quality standards of the incineration

process, irrespective of their physical state (flue gas, waste water, or solid leftovers). Simple incinerators at first have evolved into intricate operations. Every successive generation of incinerator facility uses more advanced and efficient air pollution control equipment to ensure that emissions remain within stringent limits. The need for efficient heat release recovery is continually increasing as processes progress. For this reason, we talk about WtE today. The efficiency of producing energy from trash is significantly less than that of producing energy in traditional plants that burn fossil fuels. This is brought about by a number of limitations imposed by certain characteristics of the waste utilized as fuel (such as a higher flue gas temperature exiting the boiler and a reduction in the maximum output steam pressure owing to corrosion risk) [7]. The two industries with the highest global energy intensity are power generation and transportation. The majority of these industries' energy requirements are met by pricey fossil fuels. Fossil fuel burning directly damages our ecosystem by negatively affecting the environment. Furthermore, the global energy security is being threatened by the increasing depletion of these conventional energy supplies. However, using renewable energy sources to produce electricity, heat, and other forms of biofuels has gained significant traction in national and international energy strategies. MSW has long been seen as a promising renewable energy source. The significant environmental effects of inappropriate waste management techniques and the production of electricity derived from fossil fuels can be mitigated by using MSW as an energy resource. Waste to energy (WtE) facilities are able to produce useable energy from this easily accessible and affordable renewable energy source. Consequently, by counteracting the dominance of fossil fuels in the global energy sector, WtE may offer a viable way to strengthen global energy security [8].

Classification of different WtE Technologies

The three primary mechanisms for converting WtE are physicochemical, biological, and thermochemical. Nonetheless, there are several varieties of WtE process technologies accessible, and each process technology adheres to one of the three conversion routes depicted in Figure 1.

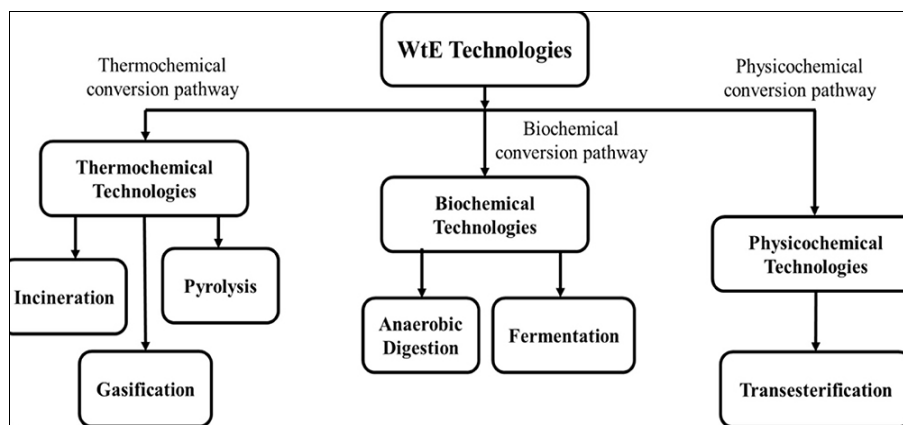


Fig 1: Classification of WtE technologies regarding conversion pathways

1. Thermochemical Technologies

Technologies that utilize high temperatures to convert various fractions of municipal solid waste (MSW) into energy, heat, and other products with added value are

known as thermochemical conversion pathways. Gasification, pyrolysis, and incineration are some of these technologies. These thermochemical WtE technologies are described in brief in the section that follows.

a. Incineration

Among WtE technologies, incineration is the most widely employed and well-established worldwide. The organic materials in MSW may be fully burned by this method, which lowers the volume of the waste and produces electricity and heat instead. The feeding system, residual disposal system, exhaust gas system, and incinerator (combustion chamber) are the essential parts of an incinerator plant. The most well-known incinerators include mass burn facilities and industrial incinerators, among others. Heat and hot flue gas, which is composed of carbon

dioxide (CO₂), nitrogen (N₂), oxygen (O₂), and water vapor, are the primary outputs of an MSW incinerator facility. Moreover, because ash makes up between 20 and 25 percent of the overall feedstock, it is also regarded as a significant end product. High-pressure steam is created during the incineration process using the heat and hot flue gases generated, and this steam is then used in a steam turbine to provide energy. Following that, a flue gas treatment facility treats the flue gases to lessen their toxicity in order to limit pollution in the environment, as can be seen in figure 2 [9].

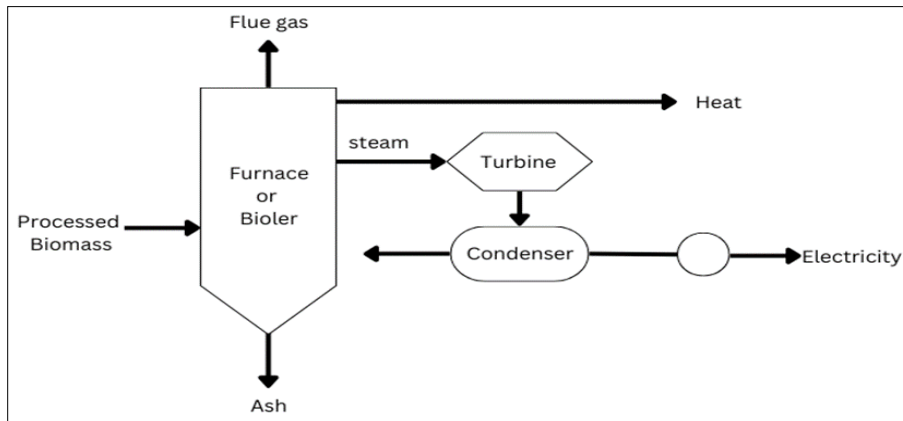


Fig 2: A schematic representation of incineration of waste material to produce energy in the form of heat and electricity

b. Gasification

Gasification is a modified form of pyrolysis in which a little quantity of steam or oxygen is present during the reaction. It is indirect combustion because, when the carbon and oxygen combine, producing heat energy. At a temperature of about 800°C, the entire process occurs. Gasification products often have a very high yield. The ideal temperature range for the gasifier is 500–1,000°C, and the ideal size distribution for the feedstock particles is tiny and consistent. There are eight distinct reactors that are suitable for gasification reactions. The reactors that fall under this category include the rotary kiln, bubbling fluidized bed reactor, entrained flow bed reactor, downdraft fixed bed reactor, updraft fixed bed

reactor, vertical shaft, and moving grate furnace. With the application of this method, combustible organic fractions and plastics from MSW may be converted into synthesis gas, a clean, highly valuable syngas. Hydrogen (H₂) and carbon monoxide (CO) are the two main ingredients of syngas. In addition to CO and H₂, there are trace quantities of methane (CH₄), nitrogen (N₂), water vapor (H₂O), and carbon dioxide (CO₂). Clean syngas from the gasification process may be utilized as valuable fuel for transportation or directly used in a gas turbine to generate combined heat and power (CHP). Additionally, it can be utilized in fertilizers and chemical industry as a supplementary raw material as can be seen in figure 3 [10].

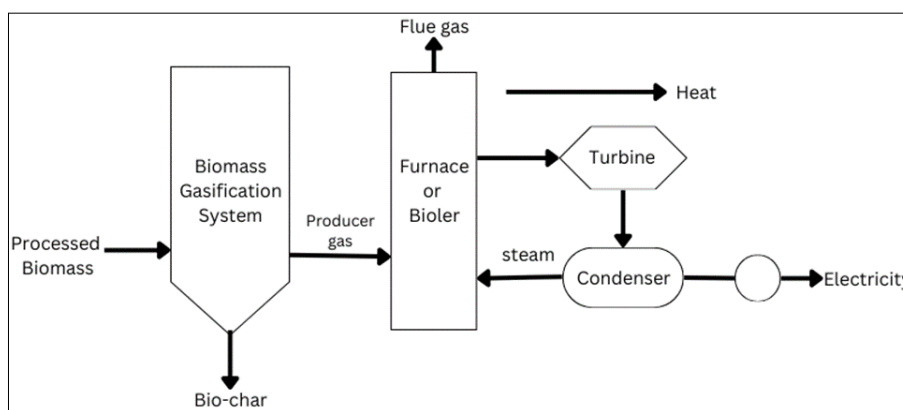


Fig 3: A schematic representation of gasification of Biomass for the production of energy in the form of heat and electricity.

c. Pyrolysis

Pyrolysis is a thermal process carried out in an oxygen-free environment. The carbonaceous portion of MSW can have up to 80% of its energy recovered by pyrolysis. These processes include flash pyrolysis, rapid, and slow. Each of the three pyrolysis processes has a separate set of operating conditions. Fluidized bed reactors are the most widely

utilized technology for pyrolysis reactions. With the use of this method, solid, liquid, and gaseous fuels (char) are produced from the carbonaceous portions of MSW. The three fuel types that are created during the pyrolysis process—gaseous, liquid, and solid—all have many characteristics with fuels derived from fossil fuels. The ethylene found in pyrolysis gas is abundant and may be

utilized to produce gasoline and alcohol. Direct use of all three pyrolysis fuels for the production of heat and electricity is possible as evident by figure 4 [11].

2. Biochemical Technologies

Biological agents or microorganisms like yeast are used in the biochemical conversion of municipal solid waste (MSW) to energy in order to transform the organic part of the trash into gaseous or liquid biofuels.

1. Anaerobic Digestion

The method of anaerobic digestion uses microorganisms to break down the organic portion of MSW in the absence of free oxygen. The bacteria that are engaged in the anaerobic digestion process at three separate stages—acidogenesis, acetogenesis, and methanogenesis—need certain growth conditions and are extremely sensitive to pH levels in order to increase the production of end products. As a result, this process happens in specialized reactors that run at particular parameters, such as a pH level and temperature that are kept constant. Sulfur reduction is a further process that is

included. It is used in order to lower the end product's sulfur level for quality assurance reasons. Nevertheless, this process also lowers the final product's yield [12]. For various kinds of feedstock, there are many kinds of reactors. Continuously stirred tank reactors are the favored method for handling food waste; plug-flow and batch reactors are utilized for other organic waste types. The anaerobic digestion process produces three distinct end products. Biogas, the primary product, is composed of 20–50% carbon dioxide (CO₂), 50–80% methane (CH₄), and trace amounts of ammonia and sulfide. Fiber and liquid digestate are the other two items produced in addition to biogas. Natural gas can be substituted by biogas from the anaerobic digestion process for CHP generating. However, compared to natural gas, biogas produces heat and electricity with less efficiency. This is due to the fact that biogas has a calorific value that is around two thirds that of natural gas. The anaerobic digestion process produces liquid digestate and fiber, which may be utilized as secondary raw materials in the fertilizer sector as evident by figure 5 [13].

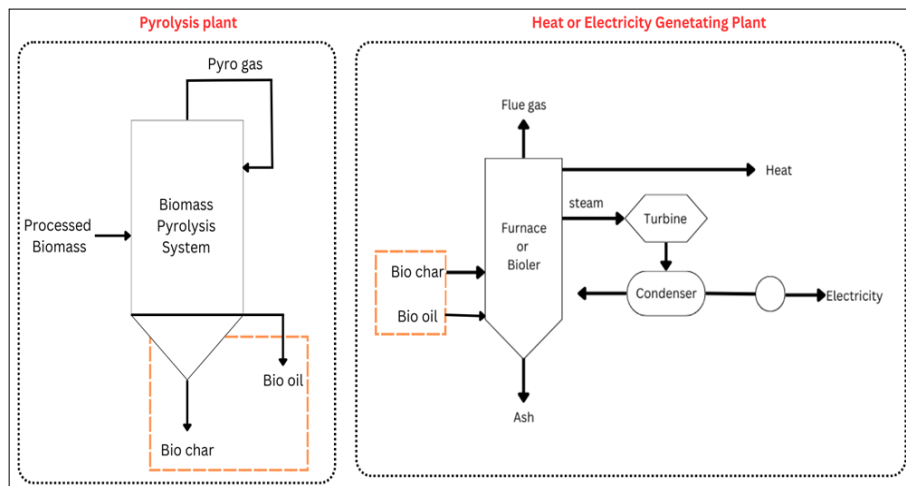


Fig 4: A schematic representation of pyrolysis of Biomass for the production of energy in the form of heat and electricity

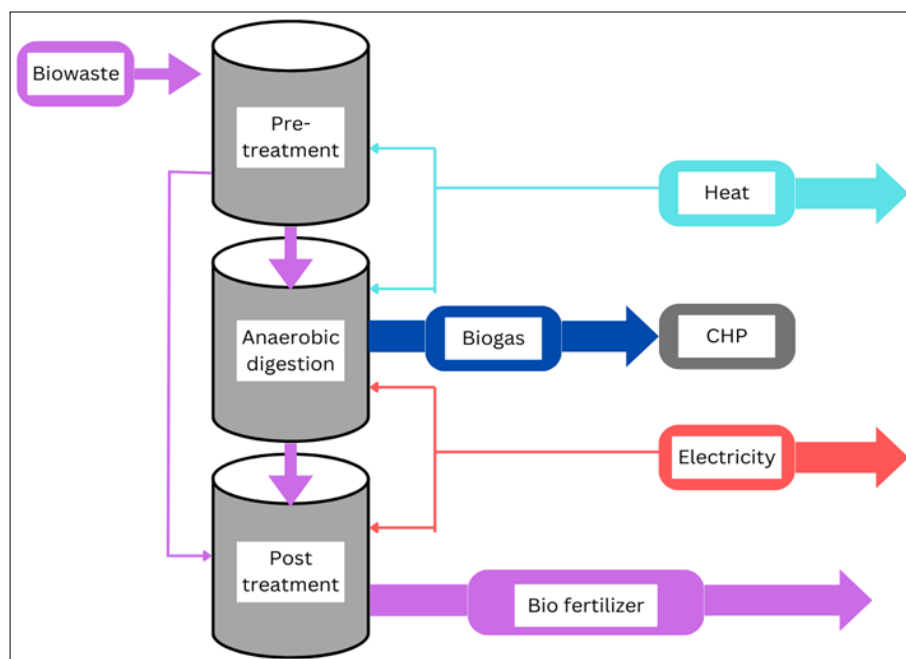


Fig 5: A schematic representation of anaerobic digestion in order to form energy from Biowaste in the form of heat and electricity along with the production of Bio fertilizer post treatment.

2. Fermentation

Microbes are also used in the fermentation process to break down organic molecules in an oxygen-free atmosphere. It is a metabolic process that turns sugar into alcohol utilizing bacteria or yeast under non-sterilized conditions. With the exception of the methanogenesis step, virtually all of the stages of anaerobic digestion are also included in the fermentation process. Therefore, liquid biofuel rather than biogas is the fermentation's final result. Distillation is a further step that separates the diluted alcohol that is produced at the conclusion of the fermentation process from the fermentation digestate. The fermentation process can be carried out in two different ways:

continuously or in batches. By maintaining a balance between the pace at which feedstock is supplied into the reactor and the rate at which it is released, the continuous process of fermentation is carried out. Because the continuous fermentation method requires smaller reactor volumes to employ larger amounts of feedstock, its initial investment, capital expenses, and operating costs are thus comparatively cheaper than those of the batch process. As an alternative to gasoline, ethanol created during fermentation can be utilized as a fuel for transportation. To get extra money, CO₂ created during fermentation can be liquefied and sold as dry ice to the processed food or confectionery industries^[14].

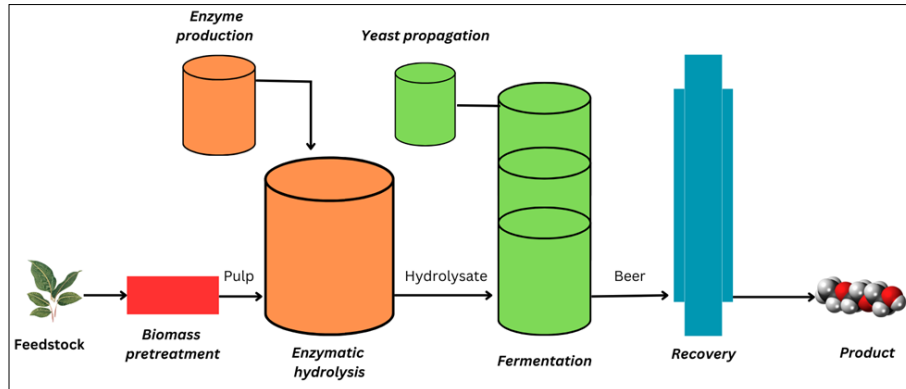


Fig 6: A schematic representation of pretreatment and fermentation of biomass in order to produce energy and associated industrially important final products.

3. Physicochemical Technologies

The most well-known WtE method, transesterification, turns food waste—more especially, used cooking oils (UCO) and animal fats—into liquid fuels by following the physicochemical conversion process. The process of transesterification creates biodiesel from the fat portions of food waste in the MSW stream. After UCO is gathered, contaminants and moisture are eliminated by screening and dehydration before the transesterification process is carried out. However, rendering facilities also process waste from slaughterhouses, turning inedible animal parts into fat and producing meat and bone meal, another value-added commodity^[15].

Compared to acid-catalyzed reactions, which take 1–8 hours to complete, alkane-catalyzed reactions complete in around 30 minutes. To turn the FFA into biodiesel in the first stage, an esterification process can be triggered by an acid catalyst. After that, the residual triglycerides can be converted into biodiesel by using an alkane catalyst through a transesterification process. Glycerol is created as a byproduct of the transesterification process, however the primary end product is biodiesel. Petrochemical diesel may be replaced by biodiesel made from UCO and animal fat, which can then be used as fuel for automobiles. Furthermore, because the biodiesel's and the by-product glycerol's higher heating values (HHVs) are so high, they may both be utilized to generate power. The rendering process yields meat and bone meal, which can be burned to recover energy or utilized as a raw material in the animal feed sector^[16].

Impact on the Environment

The generation of waste is a noteworthy adverse effect that is also continuously rising. For instance, the amount of

municipal garbage generated per person in the OECD countries rose from 415 kg in 1980 to 560 kg in 2007. Nowadays, one of the most significant approaches in the field of waste treatment is waste to energy, or WTE. This method maximizes the energy contained in flue gas while also purifying the disposal of garbage. Its significance will only grow in the future. One of the EU's most developed sectors is the waste industry. The EU has laws pertaining to the waste industry at both the national and secondary levels (particularly in the form of directives and rulings). The EU's secondary law must be in compliance with national law. Directive 2008/98/EC lays forth the fundamental processes for managing garbage. It prioritizes preventing the production of trash. On the other hand, laws differ throughout the world. If that isn't feasible, an attempt should be made to repurpose them for the same or a different goal. Only after achieving maximum recycling should disposal (treatment) be allowed, if even this is not possible^[17].

Energy use ought to be prioritized over landfilling. The European Community also considers efforts to reduce landfilling. The Directive 1999/31/EC calls for a progressive reduction in the amount of biologically degradable trash that is disposed of in municipal landfills. In comparison to 1995, 50% and 35% of this kind of trash should be reached in 2013 and 2020, respectively. The legislative enshrinement of methods for evaluating the influence of spatial development ideas and the evaluation of environmental impact assessments (EIAs) are two fundamental procedures. The laws pertaining to waste handling, which primarily concern the thermal approach as previously mentioned, have an impact on the installation of specially made technology in particular areas. Every hazardous waste incinerator needs to have an EIA completed, as well as any other incinerators whose capacity

exceeds certain thresholds. However, a number of issues pertaining to human health that result from its operation are examined. Environmental regulation continuously raises standards for the quality of byproducts of the incineration process, regardless of their state of matter (flue gas, waste water, or solid leftovers). Complex mechanisms have evolved from basic incinerators at first. Newer and more efficient air pollution control systems are incorporated into every generation of incineration plant in order to comply with rigorous emission limitations. Porteous is one source that demonstrates this development tendency. The need for efficient heat release recovery is continually increasing as processes progress. For this reason, we talk about WTE today [18].

The efficiency of producing energy from trash is significantly less than that of producing energy in traditional plants that burn fossil fuels. This is brought about by a number of limitations imposed by certain characteristics of the waste utilized as fuel. We have access to one of the cleanest and most dependable sources of energy in the form of power and heat thanks to increasingly comprehensive regulations pertaining to the operation of WTE plants. But there's another significant side effect to this tendency. The process's overall energy requirement is rising. The energy required to power electrical appliances and generate heat to sustain an ideal operating regime increases with system complexity and effectiveness. Lower heat delivery to consumers and plant power generation are the effects of this, which lowers energy production efficiencies. WTE plants are categorized as follows in relation to various waste heat usage methodologies. Because of the nation's fast expanding population and quick economic development, trash production has increased annually, we should utilize the byproducts to produce heat and energy rather than letting the trash decompose and release harmful gases [19].

Conclusion

Waste-to-energy (WtE) production stands at the intersection of waste management and energy generation, offering a dual solution to two pressing global challenges: the growing amounts of waste produced by modern societies and the urgent need for alternative, cleaner energy sources. While the technology and approach have evolved over the years, the core principle remains the same—converting waste, which would otherwise be sent to landfills, into usable energy. The primary benefit of WtE lies in its capacity to significantly reduce the volume of waste that would typically end up in landfills. Landfills are not only environmentally detrimental due to the release of methane, a potent greenhouse gas, but they also take up valuable land and pose long-term environmental risks, such as groundwater contamination. By diverting waste from these landfills, WtE technologies help reduce methane emissions and other environmental hazards associated with waste disposal. This directly contributes to global efforts to mitigate climate change and reduce the ecological footprint of urbanization and industrialization. Additionally, WtE facilities generate electricity, heat, and in some cases, usable fuel from the waste conversion process.

This represents a renewable energy source that offsets reliance on fossil fuels, reducing carbon emissions and contributing to the global energy transition towards cleaner, more sustainable sources. For countries or regions with limited natural resources or where renewable energy

infrastructure is still developing, WtE can provide a critical, dependable energy supply, contributing to energy security and diversification. Technological advancements in WtE processes have significantly improved the efficiency, safety, and environmental footprint of energy recovery from waste. Modern incineration plants, for example, are equipped with advanced pollution control systems that capture harmful emissions like dioxins, heavy metals, and particulate matter, ensuring that air pollution from these facilities is minimal and well-regulated. Technologies like gasification and pyrolysis offer even more promise by breaking down waste at high temperatures in low-oxygen environments, resulting in synthetic gases (syngas) that can be further refined into electricity, fuels, or even chemicals used in various industrial applications. Anaerobic digestion represents another technological approach, particularly effective for organic waste, where microorganisms break down the waste in an oxygen-free environment, producing biogas. This biogas, rich in methane, can be captured and used as a renewable energy source, reducing reliance on fossil natural gas. These processes contribute to a more circular economy by not only minimizing waste but also recovering valuable resources that would otherwise be lost in landfills.

In conclusion, waste-to-energy production offers a compelling solution to two of the world's most pressing issues: waste management and the need for renewable energy sources. By converting non-recyclable waste into energy, WtE reduces landfill use, cuts greenhouse gas emissions, and contributes to cleaner energy generation. Continued technological advancements and stringent environmental regulations are essential to maximizing the benefits of WtE while minimizing its drawbacks. With the right balance, WtE can be a cornerstone of a sustainable, circular economy, turning waste into a resource and contributing to a greener future for all.

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