

# Green Energy from Food Waste Conversion: A Comprehensive Review of Advanced Technologies

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The usage of renewables is growing around the world, and energy production from biomass resources, including food waste (FW) is one of the fields regarding this phenomenon. This paper explores various waste-to-energy (WtE) conversion methods, emphasizing their significance in addressing both waste management and energy production challenges. Biochemical methods such as anaerobic digestion and landfill gas production capitalize on microbial activity to generate biogas from organic waste. Additionally, bioethanol production through fermentation offers a viable route for converting lignocellulosic waste into ethanol. Combustion methods, including direct combustion and waste incineration, harness the calorific value of solid biomass resources for electricity and heat generation. The global application of WtE technologies is assessed, highlighting the increasing adoption of these methods for sustainable waste management and energy production. Comparative analyses reveal the cost-effectiveness and environmental benefits of WtE conversion methods, positioning them as essential components of the renewable energy landscape. Ultimately, this paper underscores the potential of WtE technologies to contribute to a more sustainable and resource-efficient future. Different sets of assessments demonstrate that the concept of WtE will mostly be used in sectors facing challenges in de-carbonization, the global market is going to witness a 20% rise by 2027, and the usage of biomass resources is going to be more than doubled by 2050.

**Keywords:** Pyrolysis, Gasification, Anaerobic Digestion, Fermentation, Incinerator.

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## 1. Introduction

Biomass is poised to play a significant role in the future global energy mix, offering a sustainable and renewable energy source that can contribute to reducing carbon emissions and meeting energy demands. As highlighted in various studies and reports, including those by the United Nations Intergovernmental Panel on Climate Change (IPCC) and the U.S. Department of Energy, biomass energy has the potential to become a major primary energy source globally by 2050. The utilization of biomass, particularly in hard-to-decarbonize sectors like manufacturing, heavy transportation, and aviation, can substantially lower carbon emissions. However, the transition to a more biomass-intensive energy system will require careful consideration of sustainability aspects, land use trade-offs, and technological advancements to ensure its effective integration into the energy mix. With nearly 50 million households in Europe already benefiting from sustainable bioenergy, the future entails a significant scaling up of biomass energy production and utilization to meet climate targets and ensure a more environmentally friendly and economically viable energy landscape by 2050 [1][2]. One-third of all food produced globally by weight is lost or wasted between farm and fork, which is more than 1 billion tons [3].

In the future of the global energy mix, waste food presents a significant opportunity for sustainable energy generation and reducing greenhouse gas emissions. Studies emphasize the potential for decreasing food loss and waste at various stages of the food supply chain, including at the farm, transport, retail, and consumer levels, as a means to mitigate agricultural greenhouse gas emissions. By addressing food waste through strategies like reducing retail- and consumer-level waste, substantial reductions in end-of-century warming can be achieved. Additionally, advancements in WtE technologies, such as converting municipal solid waste to biofuels, offer a promising avenue for decarbonizing energy production and contributing to a more sustainable energy landscape. The integration of innovative technologies, like WtE plants, not only helps in managing non-recyclable waste but also generates renewable energy, including heat, electricity, and fuels, thereby playing a crucial role in climate change mitigation efforts, and ensuring energy security [2][4][5].

Greenhouse gases emitted by the consumption of fossil fuels have caused catastrophic impacts on the world as the nations are desperately seeking to reach net zero the designated plan of the United Nations in 2050 to ensure that the average temperature rise of the earth does not

exceed from 1.5 °C from the beginning of the industrial revolution as well as fulfilling sustainable development goals declared by The United Nations [6]. Therefore, usage of renewable energy has become more vital to ensure energy security, and a sustainable future [7],[8]. The amount of waste generated in recent years has increased worldwide and it is going to increase by 70% in 2050 [9]. Organic fraction of municipal solid waste constitutes around 44% of the waste generated worldwide [9]. Landfilling is the most common technology in terms of waste management and is responsible for 1.9% of the greenhouse gas emissions around the world due to the high amount of methane emissions which is 80 times more powerful in terms of greenhouse gas emissions as well as carbon dioxide [10],[11]. Although there are many ways to reduce, avoid, and recycle FWs, implementation of such concepts is difficult as public education is required for less waste generation as well as separation of the different types of waste from their source of generation [12],[13]. Producing energy from food waste, therefore, is one of the most prominent methods to fulfill this concept as not only does energy usage assist the combat against climate change, but also leads to a more sustainable waste management system reducing the requirement of landfilling which causes soil, and water resources contamination as well [14],[15]. It is reported that the worldwide power generation from biomass resources has doubled over the past decade [16], and It is projected by the International Renewable Energy Agency (IRENA) that total usage of biomass energy resources is going to more than double by 2050 to reach 1.5 °C scenario [17]. These points indicate a great opportunity for power producers from biomass resources to use governmental support. Moreover, the production of fuels from the FW is going to be more prominent to meet the heating demands of the industries, as well as the sector of transportation in which electrification is facing challenges such as metal production, cement production, aviation, and maritime transportation [17].

This paper examines the methods of converting waste to energy, the related technologies, and the greatest consumers of energy from waste resources. This article aims to provide a comprehensive review of advanced technologies for converting food waste into renewable energy, highlighting innovative methods that improve energy recovery and sustainability. By systematically analyzing different waste-to-energy (WtE) methods—including thermochemical, biological, and combustion processes—this paper seeks to identify the most effective strategies for addressing the dual challenges of waste management and energy production. The purpose is to inform beneficiaries about the recent progress in WtE technologies, elucidate their environmental benefits, and emphasize their key role in the transition to a circular economy. Finally, this review aspires to inspire further research and development in the field, promoting adopting sustainable practices that contribute to a greener future.

## 2. Methods of energy harvesting from the FW

In general, methods of waste disposal that are based on energy harvesting in the world today are divided into below main groups:

1- Thermochemical methods in which a high level of temperature is used to convert the FW to new products that can be used for energy purposes, including gasification, pyrolysis, and liquefaction [18]. Fuel production in which parts of the FW that contain high levels of lipids such as waste cooking oil are refined through different steps, and fuels such as biodiesel, and aviation fuel are produced through these methods in biorefineries [19],[20].

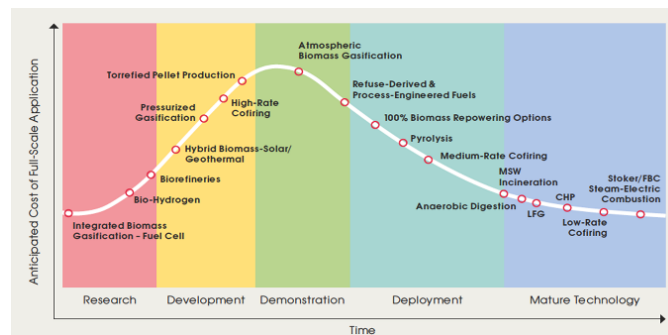
2- Biological methods based on the activity of microorganisms. The primary purpose of these systems is to eliminate the greenhouse gas emitted from the FW and produce biogas [21]. Some of the biological methods have other well-known byproducts as well such as digestate [22].

3- Combustion in which biomass resources such as FW are incinerated directly to provide energy either to provide heat or to be used for steam generation for power generation by steam turbines.

Different biomass technologies are at dissimilar development and market introduction stages, ranging from laboratory development and prototyping to fully commercialized. Figure 1 shows the maturity of WtE technologies. This figure indicates that due to better economics, and maturity, more conventional technologies such as direct combustion, and co-firing are implemented the most among technologies for turning waste into energy [23]. The data in Table 1 shows that the production of biofuels is going to witness a dramatic change in the future to fulfill the scenarios of energy transition. This table shows that usage of technologies such as biogas, and bio-methane production will be more focused upon in the future due to their ability to be used in the industries to replace natural gas as well [17].

**Table 1.** Predictions regarding energy supply for biomass resources [17]

Cases of Biomass	2020	2050-IRENA Scenario	2050-1.5°C Scenario
Traditional biomass	22	23	0
Other solid biomass cases	22	48	91
Liquid biofuels	6	19	31
Gaseous biofuels	3	7	13



**Figure 1.** WtE technologies based on maturity

### 2-1. Thermo-chemical technologies

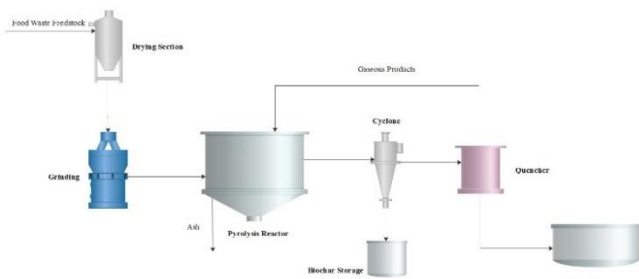
These technologies generate energy by heating the bio-waste in the presence or absence of auxiliary agents. The energy produced can be heat or secondary energy derived from energy-efficient products such as solid fuels, liquids, and gases that can be converted into kinetic or electric energy. Auxiliaries to these technologies can be steam, air, oxygen, hydrogen, and solids. The most critical heat-chemical technologies are:

- Pyrolysis: Pyrolysis in the usual way and steam pyrolysis
- Gasification: Simple gasification at standard temperature and Plasma gasification at high temperature

#### 2-1-1. Pyrolysis

Pyrolysis is a process in which organic matter is degraded by heat without oxygen. The pyrolysis reaction for biomass begins at 300 to 600 °C [24]. A variety of biomass resources such as agricultural

residue, wood waste, and FW can be used as the feedstock of the process, and a wide variety of products are produced during pyrolysis in all forms of solid, liquid, and gas. The solids formed in this process are coal (activated carbon) and ash. The resulting liquids include molar-weight materials lighter than the raw material. These include acids, alcohols, aldehydes, esters, and phenolic compounds. The following compounds are also found in gas: carbon monoxide, hydrogen, carbon dioxide, methane, ethane, ethylene, water vapor, and other minor hydrocarbons. Figure 2 shows the general concept of the pyrolysis of FW. To provide a proper feedstock for the pyrolysis reactor, drying, and grinding are necessary steps [25]. After the formation of gaseous products, they are removed from the liquid oil to be used for heating the pyrolysis reactor.



**Figure 2.** General concept of the pyrolysis process

Higher temperatures tend to support the formation of gaseous products while lower temperatures increase the chances of solid products [24]. Liquid oil produced by pyrolysis does not have the viscosity of the conventional hydrocarbons used in engines and is not capable of self-ignition. Therefore, treatment of such oil will be necessary to be used as a fuel for engines. Methods such as catalytic hydrocracking are sufficient for this intention [26],[27]. There are three forms of pyrolysis systems:

- 1- Slow pyrolysis in which the heating rate is not as fast as the other methods, and the main focus is on charcoal production [24].
- 2- Fast pyrolysis in which the residence time of the biomass is between 0.5 to 10 seconds, and the heating rate is between 10 to 200 °C/s [24].
- 3- Flash pyrolysis in which residence time is less than 0.5 seconds, and the heating rate is between 1000 to 10000 °C/s [24].

The focus of fast, and flash pyrolysis methods is upon liquid biofuel production, and due to the importance of liquid biomass resources as reported earlier, this technology is going to have a great potential for energy purposes from FW treatment. Liquefied fuel can be refined to be used for various usages including transportation in which light oil can be used as additives for personal vehicles, while refined heavy oil produced by pyrolysis can be used for aviation and maritime transportation. Because these sections face challenges for decarbonization through electrification, refined liquid fuel produced by this method can provide a great option for this purpose.

In industrial conditions, pyrolysis uses different reactor types, each appropriate for various operational scales and feedstock characteristics.

### 2-1-1-1. Types of Pyrolysis Reactors

1. Fixed-Bed Reactors: These are simple and cost-effective, where the feedstock is placed in a static bed. They are suitable for small to medium-scale operations and can process a variety of food waste types [28].
2. Fluidized-Bed Reactors: In these reactors, the feedstock is suspended in a gas stream, allowing for efficient heat transfer and

uniform heating. This design is ideal for large-scale operations and can handle consistent feedstock like food waste [29].

3. Rotary Kiln Reactors: These cylindrical, rotating reactors are effective for continuous processing and can accommodate heterogeneous feedstocks, making them suitable for mixed food waste and other types of organic waste [28][29].

4. Auger Reactors: Using a screw mechanism to transport feedstock through a heated chamber, auger reactors provide good control over the heating rate and residence time, making them suitable for different food waste types [29].

### 2-1-1-2. Suitable Types of Food Waste for Pyrolysis

Pyrolysis can effectively process a diverse range of food waste, including:

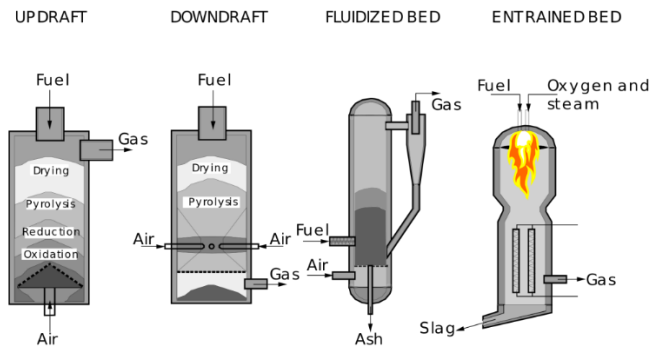
- Fruit and Vegetable Waste: Peels, cores, and other byproducts from processing fruits and vegetables.
- Meat and Fish Processing Waste: Includes bones and scraps from meat and fish processing industries.
- Dairy Waste: Such as whey and curds from cheese production.
- Bakery Waste: Unsold or expired bread and pastries.
- Used Cooking Oils: Waste oils from food preparation in restaurants and food processing facilities [28][29].

The selection of feedstock can significantly influence the yield and quality of pyrolysis products. For optimal results, pretreatment methods such as drying, and size reduction may be employed to enhance the feedstock characteristics before pyrolysis [30].

## 2-1-2. Gasification

### 2-1-2-1. Conventional gasification

The gasification process has the same concept as the pyrolysis process in terms of using heat for fuel production but has a higher level of temperature (500 °C-900°C), therefore being preferable for gaseous products [31]. Chemical reactions lead to the formation of syngas which mostly contain hydrogen, carbon monoxide, carbon dioxide, methane, and water vapor while ash is produced as well [32]. There are four types of gasification technologies for conventional gasification: 1- Updraft gasification 2- Downdraft gasification 3- Fluidized bed gasification 4- Entrained bed gasification. Figure 3 depicts the mechanism of each type of conventional gasification technologies. In these technologies, biomass waste materials such as FW will enter as the fuel, and a part of the feedstock is oxidized to provide the energy required for the gasification process [31]. Conventional gasification technologies are mature enough to be used to produce bio-hydrogen. The growing importance of clean hydrogen for the decarbonization of several hard-to-abate industries such as metal production, refineries, cement, and renewable fuels for transportation makes conventional gasification technologies a viable option [33]. Moreover, the usage of syngas produced by gasification can lead to cleaner production of chemicals compared to the conventional methods which use natural gas for the production of syngas [34].



**Figure 3.** Conventional gasification technologies [35]

### 2-1-2-2 Plasma gasification

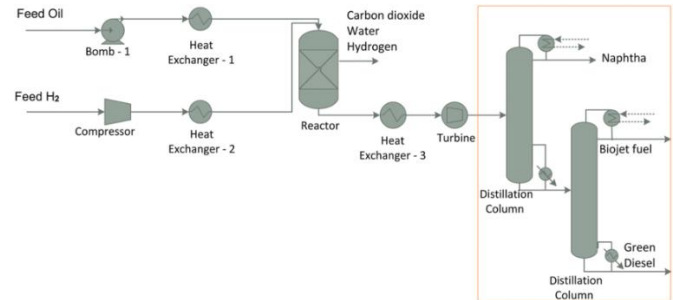
Plasma gasification is one of the new technologies in which ionized gas plasma produced by electric current is used instead of oxidation of the biomass feedstock in gasification reactors [36]. Plasma consists of a mixture of electrons, ions, and neutral particles but is generally electrically neutral.

Plasma can have a wide range of temperatures making it suitable for various subjects such as surface coating, waste destruction, and gas treatment [37]. In plasma gasification, the gasifying reactor operates in the range between 1500, to 5000 °C [36].

The plasma system boasts several key characteristics that make it a versatile and effective waste management solution. Due to the sustainable nature of this technology, it has been presented as a viable option for waste treatment in the future [38]. Syngas produced by this method has the same benefits that are mentioned for conventional gasification systems. The system is designed to be compact, allowing small, removable trailer systems to be constructed. A wide range of feedstock, moreover, can be used for this technology, eliminating the need for separating solid waste [36]. Although the initial investment and maintenance costs are relatively high, usage of this technology has been on the rise for multiple purposes such as the production of sustainable aviation fuel as British Airways is seeking to produce clean fuel from waste through this technology for their efforts in decarbonization [36].

### 2-1-3. Bio-jet fuel production from cooking oil waste

Due to great trends of electrification in ordinary transportation such as personal vehicles, and trucks, usage of biodiesel is going to be dramatically decreased for vehicle usage [17]. Therefore, the usage of bio-based oils for sections such as aviation, and maritime transportation has gained attraction throughout these years as Neste which is a famous oil refinery company has greatly invested in the production of sustainable aviation fuel from bio-based oils including cooking oil waste, and the airline systems of multiple countries such as Singapore, England, and other European countries have started using bio-jet to reduce the emissions of the aviation industry [39]. Although 90% of the bio-jet fuel is produced from oil derived from agricultural products such as soybeans, palm, rapeseed, and corn, the usage of animal fat and waste cooking oil to produce bio-jet oil still takes 10% of the bio-jet oil, providing a great option for cooking oil waste management as well as the FW with high levels of lipid. Figure depicts the production of bio-jet production from cooking oil waste in which cooking oil waste is reformed by the addition of renewable hydrogen which purifies the waste oil from oxygen, and high-grade bio-jet oil is finally from renewable diesel as well as naphtha which is the byproduct of the bio-jet production process [40].



**Figure 4.** The general process of bio-jet fuel production from waste cooking oil [40]

## 2-2. Biochemical processes

In these technologies, energy producers are products created by the metabolism of living organisms and used as fuel because of their high calorific value. Methane gas and ethyl alcohol (ethanol) are the most critical products to be used as energy source [41]. The anaerobic digestion process produces methane gas and ethanol by the alcoholic fermentation process.

### 2-2-1. Anaerobic Digestion

The process of decomposing biomass resources by bacteria is in the absence of air, in which methane and by-products are produced with a medium thermal value (biogas) inside a reactor called a digester [42],[43]. This technology consists of four different steps:

1- Hydrolysis in which the complex structure of the feedstock is broken through microbial activity with the presence of water [42],[43].

2- Acidogenesis in which the materials produced in the hydrolysis are further broken into organic acids, and alcohols by acetogenic bacteria [42],[43].

3- Acetogenesis in which acetogenic bacteria turn organic acids, and alcohols produced by the previous step into hydrogen, carbon dioxide, and acetic acid [42],[43].

4- Methanogenesis in which methane is produced by the methanogenic bacteria through the products of the previous part [42],[43].

The efficiency of the digestive process is also affected by the digestive temperature, pH, carbon-to-nitrogen ratio of the feedstock, water content of the feedstock, retention time, and toxicity to the bacteria. While the first two steps require high temperatures and are not sensitive to the level of pH, acetogenic, and methanogenic sets of bacteria will have higher efficiency at higher levels of pH and lower temperatures [44],[45].

A great range of biomass resources such as dairy manure, organic fraction of wastewater, agricultural residue, and organic fraction of solid waste can be used as the feedstock of this process [42], and processes such as drying are not required for anaerobic digestion, unlike technologies such as gasification, and pyrolysis. Production of digested, which is the solid, and liquid fraction of the products of anaerobic digestion makes this technology a highly sustainable technology for waste treatment because digested can be used as organic fertilizer, fulfilling the concept of circular economy [46]. There are several categories by which the anaerobic digestion process can be divided into:

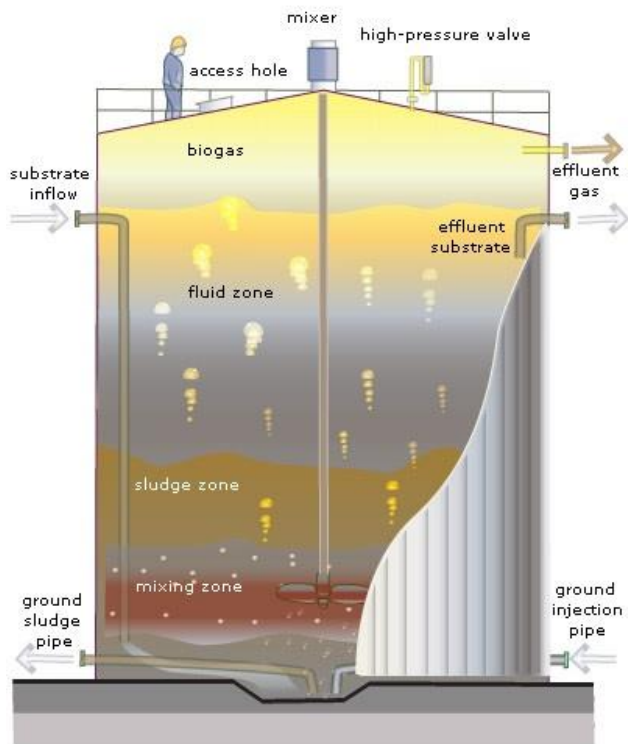
1- Temperature in which there are psychrophilic, mesophilic, and thermophilic methods. The first method operates in temperatures lower than 20 °C. The second method operates between 35 to 38 °C, and the third method operates between 50 to 55 °C [47]. Although the

thermophilic process leads to higher efficiency due to a higher level of destruction of the FW components as well as more biogas production, the mesophilic process is more used on the industrial scale due to difficulties of the thermophilic approach such as inhibition due to high levels of ammonia formation [47].

2- The water content of the feedstock in which the process will be called dry if the water content of the feedstock is between 60 to 80% while in the wet type, the water percentage of the feedstock is between 80% and 90% [48].

3- The number of reactors that can be increased for optimization of the process. While traditional forms of anaerobic digestion have only one reactor, a two-reactors system is proven to be more efficient because the first two stages of anaerobic digestion occur inside the first reactor, and the latter stages occur in the second reactor. This concept increases the rate of microbial activities for each step. However, such a concept has not been commercially implemented due to high capital costs. Moreover, a two-step process can be used for hydrogen production as well [45].

Figure shows the general concept of the anaerobic digestion process inside a continuous stirred tank reactor, in which the biogas is harnessed through upper sections. In terms of economy, it is biogas management that takes the highest level of costs regarding capital investments. From 40 to 50% of the capital costs of an anaerobic digestion complex is for combined heat, and power generation units if it is used for the usage of biogas [49], and more capital costs will be imposed upon an anaerobic digestion complex if a bio-methane production process is considered instead of a CHP unit.



**Figure 5.** Scheme of anaerobic digestion of municipal waste

Biogas is also called marsh gas. It contains two significant components of methane (and a few other hydrocarbons), carbon dioxide, and minor impurities such as hydrogen sulfide, vapor, etc [42]. This gas mixture has a thermal value of 16-28 MJ/m<sup>3</sup> [50], and can be used either inside reciprocating engines for combined

production of power, and steam as well as vehicle engines. Biogas, moreover, can be upgraded to bio-methane which is an ideal alternative to natural gas [50]. Reports of IRENA indicate that bio-methane has a great potential for decarbonization of the hard-to-abate industries due to having the same characteristics as natural gas. Moreover, carbon dioxide which is removed from the biogas in bio-methane production can be used as a feedstock for further fuel, and chemical production through its reaction with renewable hydrogen [51]. It is also worth mentioning that these issues are important regarding the maintenance of an anaerobic digestion unit:

- The level of pH
- The level of ammonia
- The level of hydrogen sulfide (H<sub>2</sub>S) in biogas
- Complete removal of the feedstock after the operation

### 2-2-2. Landfill gas production process

Although landfilling has numerous devastating impacts, it will widely be used across the world. It is, therefore, necessary to capture the greenhouse gas emitted through this method which is the same biogas produced by anaerobic digestion technology. Landfill gas production at the landfill begins between 2 and 6 months after the landfill, and this delay depends on the percentage of degradable organic matter in the waste, the moisture content of the waste, how the material is distributed in the landfill, the amount of water permeable to the landfill, and the ambient temperature. The percentage of methane in landfill gas often reaches a steady state after six months to one year. Gas production peaks about one to two years after its inception and then decelerates and reaches near zero over many years. This time depends on the decomposition rate of organic matter and gas production.

### 2-2-3. Bioethanol production (Fermentation)

Production of bioethanol is another major biochemical method of turning waste into energy sources [52]. FW that contain lignocellulose, as well as other forms of sugar such as xylose, cellulose, etc can be used for bioethanol production [52]. This process has four major steps:

1- Pretreatment in which reactivity of the entering feedstock will be increased for the further steps as the simpler cellulosic compound will be more available, and the polymers existing in the feedstock are broken for the further steps. Traditional methods of pretreatment such as chemical methods are the most common method in which different acid materials are used for this intention [52].

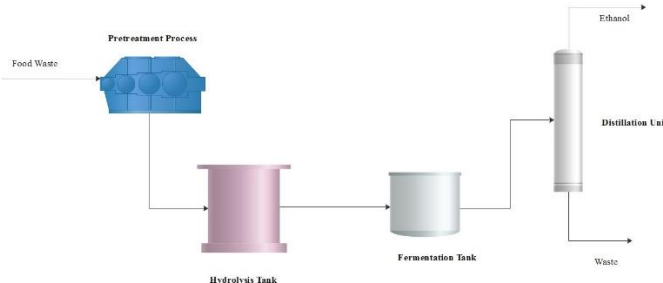
2- Hydrolysis in which sugar monomers are produced in higher purity for the efficiency of the further steps [52]. Usage of the acid-catalyzed method is the most conventional method for this step which can be in the terms of diluted acids or concentrated ones such as sulfuric acid, and hydrochloric acid. Diluted acid will be used in the first step while concentrated acids will be used in the second step of this method of hydrolysis [52]. However, enzyme-catalytic hydrolysis has gained attraction due to eliminating the difficulties of the acid-catalyzed methods. However, enzyme-based hydrolysis is expensive due to the high costs of enzymes [52].

3- Fermentation in which ethanol, gases, and acid will be produced from the monomer sugars produced by the previous step. Issues such as temperature, the level of pH, and fermentation time have a great impact on the amount of ethanol produced in this stage [52].

4- Ethanol recovery in which water content is reduced through processes such as distillation, and high-purity ethanol is produced as the product [52].

Although this technology is mostly used in industries that produce FW with a high level of cellulose, the production of bioethanol is

gaining traction due to its ability to be added to conventional fuels such as aviation, and maritime fuel. Moreover, bioethanol is one of the most viable options for the future of these sectors on their road to de-carbonization [51]. Moreover, bioethanol produced by the food industries can be used to provide their required energy as well. The usage of FW, therefore, is gaining tracks for bioethanol production (Figure 6).



**Figure 6.** Fermentation process for bioethanol production complex in general

## 2-3. Combustion methods

### 2-3-1. Direct combustion

In this technology, solid biomass resources such as forestry, agricultural waste, FW, and municipal waste are directly burned in specific boilers, and the resulting heat is used to generate electricity, heat, or electricity and heat. This group's most crucial electricity generation technologies are waste and wood incinerators.

From a technical and practical point of view, direct combustion technology can be divided into the following two applications:

1. Home applications: This use is limited in scale and is used to meet the needs of residential units and small businesses in rural communities. The significant needs of these consumers are cooking, the heat needed for residential heating and hot water consumption, and some other limited applications, such as conventional small-scale furnaces (pottery, forging, dyeing)

2. Industrial applications: In this context, biomass combustion is considered on a larger scale. Suitable biomass sources for this use include wood and wood wastes, agricultural and horticultural residues (straw, bran, dry leaves of shoots, twigs, straw, bark of tree stems), and municipal waste. Combustion of these fuels results in heat generation, and the released energy can be used for heating in industries such as food, cement, concrete production, and chemicals.

### 2-3-2. Waste incinerator

In general, waste incineration is a technology in which the waste is burnt through different steps to produce steam for production of power, and heating purposes. Waste incineration has great potential in areas that do not have high standards of waste separation from its origin, or the amount of land is limited while the amount of waste is high. This method is excellent for waste materials, and industries in which recycling methods are not applicable as well such as hospital wastes [53].

Municipal solid wastes inherently have thermal energy due to carbon in their building. In Europe, unprocessed municipal solid waste usually has a thermal value of about 8,000 to 13,000 kJ / kg (5600-3400) Btu per pound (as a general rule, a waste incinerator, After deducting the internal energy consumption of the plant, they can generate 450 to 500 kWh of electricity per ton of waste (with a thermal value of about 9,000 kJ / kg), which is present in 24 tons of waste after heat treatment digestion and conversion to electricity can provide the annual energy needed for a home in developed countries

[54].

Several protection measures ought to be implemented for a standard waste incineration facility such as: 1- An air pollution control system to refine the incinerator's gas product (especially the flue gas) depending on the feedstock, and environmental regulations [55].

2- Ash and sludge collection are mechanically collected and cooled (first deposited by water and then driven out of the incinerator), and electric magnets are used to separate recyclable materials such as iron and aluminum.

Different waste incinerators are manufactured with different volumes that can be used for different types of waste depending on the type of waste, moisture, waste volume, amount of heat produced, etc.

### 2-3-2-1. Different parts of a waste incinerator and combustion stages

The incinerator consists of a burner that ignites the available fuel and other combustible materials contained in the waste in a combustion chamber. The efficiency and process of combustion depend on the three main factors of the combustion chamber: 1- Temperature 2- Material retention time and, 3- Mixing materials

The primary combustion chamber or furnace into which the waste is disposed of and during the initial stages of combustion. In many waste incineration systems, the gases generated during the incineration process as incomplete combustion by-products are transferred to the second combustion chamber designed to increase the efficiency of degradation of incomplete combustion by-products or waste incineration. The remaining ash in the bottom of the combustion chamber is gravity-fired and then cooled over time. The exhaust gas from the second combustion chamber is driven through an air pollution control system that may include various parts.

The variety of parts of this system depends on:

- The type of pollutants on which the burning operation is performed
- Waste compounds
- Furnace design

Continuous maintenance of the machine is an essential step and includes:

- Weekly inspection, cleaning, and service of parts according to a continuous plan by qualified persons and institutions to provide these services.
- Repairing the machine's location modernizing the furnace, crane, and other parts of the machine as needed, which is generally necessary in a few years to rebuild and modernize the machine. For maintenance and current repairs. Reproducing refractory bricks, insulation, burners, and other worn-out components is necessary. Replacement of some parts of the machine requires tools such as a welding machine, drill machine, and other essentials.

## 3. Application of waste, and the status of WtE in the world

Usage of the WtE concept is widespread around the world, and it is projected that the usage of the supplied bioenergy is going to be more than doubled by 2050, signaling a great deal of potential for WtE plants around the world in the future [17].

Table 2 demonstrates the incineration, landfilling, and recycling percentages among several European countries as well as South Korea, and the United States for the method of waste management [56]. Table 3 shows the capacity of WtE facilities among the studied countries.

**Table 2.** Methods of waste treatment among different countries [56]

Country of Study	Landfilling (%)	Incineration (%)	Recycling (%)
US	49.5	11.7	23.4
South Korea	11.5	22	60.7
Germany	0.8	32.2	47.7
UK	14.3	39.3	26
France	18	38	22.5
Sweden	0.6	60	20
Netherland	1	41.9	27.6
Austria	2.1	4.4	26.8

The results of these tables indicate that the primary goal of the waste management system is upon usage of methods other than landfilling due to their higher status in terms of sustainability. However, it does not decrease the importance of using all of the technologies that are available to establish a great waste management system as well as a well-established WtE system in a country. South Korea is the prime example of such a statement as they have one of the highest rates for energy production from waste per capita while having the best waste management system worldwide, and although the amount of landfilling is higher for this country among other studied cases, usage of a wide range of technologies has enabled them to be a great example of well-established WtE systems around the world.

**Table 3.** *WtE* parameters in several countries [57],[58],[59].

	Capacity (MW)	Energy production per capita (MW/million people)
US	2051	6.2
South Korea	1592	30.8
Germany	1023	12.2
UK	773	11.5
France	625	9.2
Netherland	394	22.2
Sweden	336	32.03
Austria	245	27.09

Sweden has the highest amount of WtE per capita among the studied countries while having the lowest amount of landfilling among the studied cases. These issues indicate that implementation of well-thought policies regarding waste, and energy can lead to more sustainable, and cleaner energies at the same time as these two countries are among the best in terms of waste management.

#### 4. Comparison of WtE conversion methods with each other, and other sources of renewable energy

Figure 4 depicts the amount of power generated by different sources in 2020, 2030, and 2050 in two scenarios. The first scenario is considered by IRENA, while the second one is the 1.5 °C scenario in which net carbon emissions will reach zero by 2050. This bar chart indicates that although the usage of biomass resources including WtE technologies is going to increase in the future, power generation is still going to be dominated by solar, wind, and

hydroelectric resources among renewable sources [17].

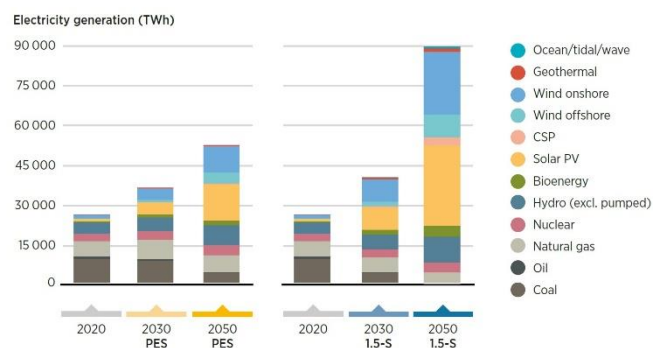
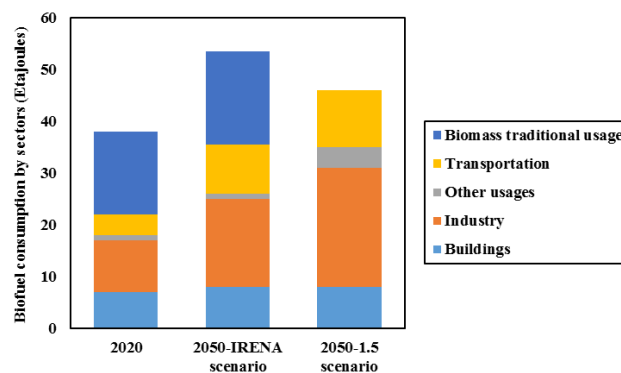
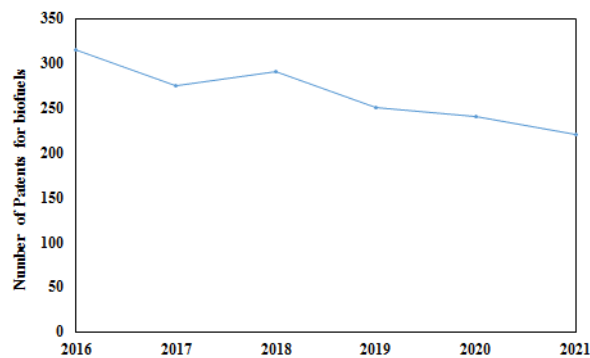
**Figure 7.** The outlook of power generation in the future

Figure 8 shows that different scenarios have pinpointed the importance of the biofuel industry for the decarbonization of the industries as well as transportation.

**Figure 8.** The outlook of bioenergy consumption in the future in different sectors

To determine the status of a particular technology in its lifecycle, the number of articles, patents, and trademarks associated with it can be examined in recent years, and its life cycle can be determined, for example, if the number of articles related to the technology concerned is high. Figure 9 shows that the number of patents has decreased in recent years [60]. However, the economic parameters regarding the biofuel industry on a global scale in Figure 0 indicates that this industry is going to witness a significant expansion in the future [61].

**Figure 9.** The number of patents for biofuels in recent years

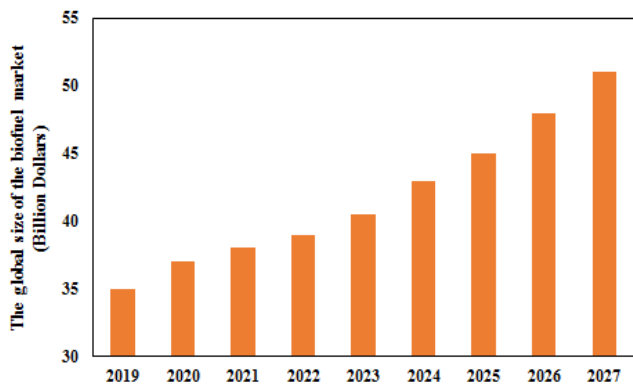


Figure 10. The economic size of the biofuel industry

Considering the above two figures and the concept of the life cycle in technologies, it can be concluded that the technologies for the conversion of WtE have reached their maturity in terms of technological innovations, and the commercial aspects of the bioenergy industry are the main field for growth, nowadays. The diagram below shows the levelized cost of electricity generated through waste conversion to energy.

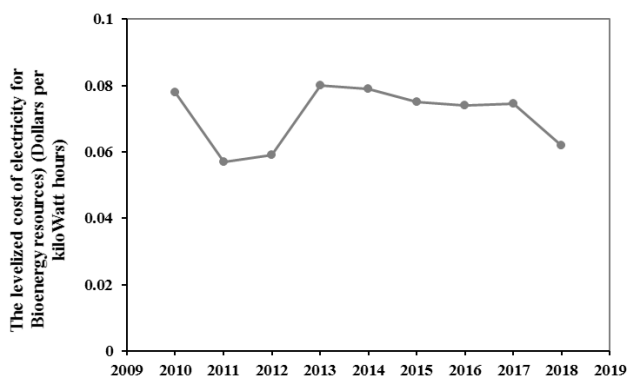


Figure 11. The levelized cost of electricity for biomass resources

As the technology evolves, this change in price for the finished price is relatively low, almost 0.06\$ per kWh. The following table compares it with other conventional renewable technologies.

Table 4. Levelized costs of electricity for other renewable energy resources

Energy Type	LCOE (USD per kWh)
Photovoltaic	0.08
Geothermal	0.07
Hydropower (Large Scale)	0.04
Wind	0.055

The equilibrium cost of converting waste to solar and geothermal energy is lower. However, the critical thing about photovoltaic energy is that it is still going through its growth period, and it is predicted that the price will decline in the coming years, increasing the approach to photovoltaic energy. These data indicate that usage of the concept of the WtE is an effective method for power generation, and due to the prevention of methane emissions

caused by landfills [11], this concept has a high standard regarding environmental issues as high standards for facilities such as waste incinerators improve the environmental aspects of WtE centers.

The energy recovery efficiencies for various waste disposal methods based on energy harvesting are as follows:

#### 1. Thermochemical Methods:

- Gasification: Energy recovery can vary widely, but it often achieves efficiencies around 70-90%, depending on the feedstock and operational conditions.

- Pyrolysis: Energy recovery efficiencies typically range from 50-80%. The specific yield can depend on factors such as temperature and the type of biomass used.

- Liquefaction: This method can produce liquid fuels with energy recovery efficiencies that can exceed 80%, depending on the biomass type and process conditions.

#### 2. Biological Methods:

- Anaerobic Digestion (AD): This method is noted for its high energy recovery efficiency, generally around 81% for food waste, with some studies reporting efficiencies as high as 93.2% when integrated with hydrothermal carbonization (HTC) at optimal temperatures [62][63].

- Hydrothermal Carbonization (HTC): When combined with AD, HTC can achieve energy recovery efficiencies of 85-93% at various temperatures, enhancing overall energy recovery from organic waste [62][64].

#### 3. Combustion:

- Direct Combustion: Energy recovery from combustion of biomass, including food waste, typically yields around 15-20 MJ/kg, depending on the moisture content and type of biomass. Overall energy recovery efficiencies can vary, often falling between 70-90% based on the combustion technology used.

These methods collectively demonstrate significant potential for energy recovery from food waste, contributing to sustainable waste management and energy production strategies.

## 5. Comparison of Waste-to-Energy Methods

Waste-to-energy (WtE) technologies offer various approaches for converting food waste into energy, each with distinct advantages and limitations. Below is a comparative analysis of the primary methods: thermochemical methods (including pyrolysis and gasification), biological methods (such as anaerobic digestion), and combustion.

### 5-1. Thermochemical Methods

- Energy Recovery: Generally high, with efficiencies ranging from 50-90%, depending on the specific process and feedstock.

- Products: Produces biochar, bio-oil, and syngas, which can be further refined into fuels or chemicals.

- Feedstock Flexibility: Capable of processing a wide variety of organic materials, including mixed and contaminated waste.

- Operational Complexity: Requires advanced technology and control systems, which can increase capital and operational costs.

- Environmental Impact: Can produce emissions and require proper management of byproducts; however, they can reduce the volume of waste significantly.

### 5-2. Biological Methods

- Energy Recovery: Typically, lower than thermochemical methods, with anaerobic digestion achieving efficiencies around 81-93% for

food waste.

- Products: Primarily generates biogas (methane and carbon dioxide) and digestate, which can be used as fertilizer.
- Feedstock Specificity: Best suited for organic materials with high moisture content; may require preprocessing for optimal performance.
- Operational Complexity: Generally simpler and more cost-effective than thermochemical methods but may require longer processing times.
- Environmental Impact: Considered environmentally friendly, as it reduces greenhouse gas emissions and produces renewable energy.

### 5-3. Combustion

- Energy Recovery: Yields energy recovery efficiencies of about 70-90%, depending on the technology used.
- Products: Primarily generates heat and electricity, with ash as a byproduct.
- Feedstock Flexibility: Can handle a wide range of biomass, including food waste, but may require preprocessing to reduce moisture content.
- Operational Complexity: Relatively straightforward technology but requires effective emissions control systems to manage air pollutants.
- Environmental Impact: Can contribute to air pollution if not properly managed, but modern systems are equipped with technologies to minimize emissions.

**Table 5.** Summary of Comparison

Method	Energy Recovery Efficiency	Main Products	Feedstock Flexibility	Operational Complexity
Thermo-chemical	50-90%	Biochar, Bio-oil, Syngas	High	High
Biological	81-93%	Biogas, Digestate	Moderate	Low
Combustion	70-90%	Heat, Electricity	High	Moderate

The choice of the WtE method depends on various factors, including the type of feedstock, desired end products, economic considerations, and environmental goals. Each method has its strengths and weaknesses, making it essential to evaluate them in the context of specific waste management and energy production needs.

### 6. Conclusion

The general concept of making energy resources from FW is investigated in this paper. Different sets of technologies have been investigated including pyrolysis, gasification, anaerobic digestion, bioethanol production, combustion methods, and bio-jet production. Pyrolysis and gasification are based on heating the FW to high temperatures to produce liquid and gaseous fuels, respectively. Anaerobic digestion is based on the production of bio-methane, while combustion methods are based on burning the waste to

produce steam for heat, and power. Bio-jet fuel is found to be a promising method due to industrial usage by international companies. The results of studying different countries show that the implementation of well-placed policies as well as the usage of different ranges of technologies will help the countries to become efficient in terms of waste management, and energy production from waste, simultaneously. The results, moreover, show that although the leveled costs of power production from biomass energy do not differ from other sources of renewable energy, biomass energy is not going to be as attractive as other renewable sources methods in terms of power generation. However, industrial, and transportation sectors will use more of the biomass energy potential in the future.

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