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Environmental and Economic Analysis of Energy-from-Food Waste Systems: A Life-Cycle Evaluation Approach

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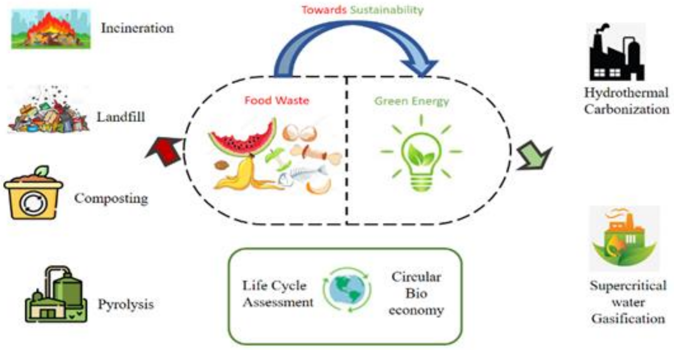
Abstract Food waste is a major problem at every stage of the value chain, from harvest to processing, storage, and consumption. This issue is made worse by the quickening rate of industrialization and population expansion. Food waste is often burned to recover some thermal energy or allowed to degrade naturally, which contaminates the environment and reduces its value. This study presents a comprehensive environmental and economic analysis of energy-from-food waste systems using a life-cycle evaluation approach. With the growing concern over food waste management and the increasing demand for sustainable energy solutions, there is a pressing need to assess the environmental and economic implications of converting food waste into energy. Making bio-based liquid or gaseous fuels from food waste is one possible approach. By doing this, we simultaneously address two very important issues: cutting waste and supplying the increasing need for gasoline. Additionally, this strategy lessens the rapid depletion of fossil fuel reserves. evaluation of the most recent garbage disposal technology is crucial in this situation. For fuel conversion to be effective, factors for process intensification must be identified while taking logistical feasibility into account. New technologies like supercritical water gasification and hydrothermal carbonization are being assessed alongside more traditional techniques including biochemical processes, landfilling, incineration, composting, anaerobic digestion, and pyrolysis. Our comprehension of their environmental effect is guided by critical evaluations based on life cycle analysis, multi-objective optimization, and circular bio-economics.

Keywords Life Cycle Analysis, Food waste, Energy, Sustainability, Biofuels

Graphical Abstract



1. Introduction

The most fundamental necessity for human life is food. In between post-harvest and consumer, most of the food we eat is either lost or wasted. The majority of food waste is organic waste, which comes from a variety of places, such as farms, factories, kitchens, and eateries. A reported 931 million tons of food, or 17% of the entire amount of food available, are reportedly wasted each year by consumers, restaurants, and merchants, based on what the UN (United Nations says Environmental The Food Waste Index Report 2021 from the Programmed (UNEP) (Hamish et al., 2021) [1]. According to a different FAO assessment, in the next 25 years, there will likely be an increase in the amount of food wasted, with fresh veggies losing out to dairy and meat goods by approximately 1.3 billion tons (Uçkun Kiran et al., 2014) [2]. According to a Boston Consulting Group study, 66 tons of food would be lost every second, representing a one-third increase in annual food waste, by 2030 (Martin-Rios et al., 2020) [3]. Due to an ignorance of the terms "best before" and "use by," which are used to assess shelf life, a survey carried out in Finland revealed that families produced more than 50% of the food waste (Filimonau & De Coteau, 2019; (Sridhar, Ponnuchamy, et al., 2021) [4,5]. With more leftovers and people dying from a lack of food, the continuing coronavirus epidemic has now negatively impacted the food crisis and insecurity. Growing worries about waste creation and management, have indirectly put a tremendous amount of pressure on the world's food supply. Global awareness of food waste has considerably risen as a result of economic and demographic growth. As stated by the FAO and the World Bank, Annually, around 1.33 billion tons of food are lost or squandered, and this amount will increase to 2.2 billion tons if current trends continue (Su et al., 2020; Dhara et al., 2024) [6,7]. The distribution of worldwide food waste (%) along the worth cycle from manufacturing to consumption is shown in Figure 1 (Safa Barraza, 2018) [8]. It was shown that in higher-income countries, dairy products make up around 17% of food waste, whereas roots and tubers account for 13% of waste in lower-income nations (Chen et al., 2020) [9]. Inefficient production processes, weak supply chains, high customer expectations, unfavorable agricultural circumstances, and governmental limitations are some of the factors that contribute to food waste internationally (Sridhar, Ponnuchamy, et al., 2021) [5]. Even though there is enough food produced every day to feed the majority of the world's population, procedural technologies, and effective waste recycling and management continue to be issued. Food waste can be disposed of at dump yards or burned along with other municipal garbage, according to traditional methods of disposal. But over time, this process produces large amounts of dioxins and hazardous gases, which pollute the air and release chemicals. According to studies, the food business contributes 26% of greenhouse gas emissions that cause climate change (Martin-Rios et al., 2020; Poore & Nemecek, 2018; Girotto et al., 2015; Torres-León et al., 2018; Adnan et al., 2024) [3,10,11,12,13]. Furthermore, the hazardous gases methane, carbon monoxide, and ammonia that are produced by these food wastes threaten to pollute groundwater(He et al., 2018; Selvam et al., 2010)[14,15] . Therefore, careful management of these wastes is required to ensure their safe disposal. Although reducing volume is a good alternative, traditional techniques like reduce, reuse, recycle, and recover need to be used more carefully (Ahamed et al., 2016) [16]. Researchers are focusing on fuels that are sustainable and low in energy made from used cooking oils and substances high in lipids, and non-edible oils because of environmental concerns and the depletion of fossil resources. These alternative fuels have demonstrated excellent performance in terms of efficiency as well as replacing petroleum (Gnanaprakasam et al., 2013; Khan et al., 2014) [17,18].

For instance, studies on the use of food waste lipids produced 90% biodiesel in 24 hours (Karmee et al., 2015)[19]. Additionally, food waste may be transformed more simply and with less processing than other feedstocks (Dhara & Fayshal., 2024) [20]. They may also be used as animal feed since they are high in proteins, carbs, lignin, and fats and produce very little waste. The production of biofuels or clean energy fuels that further the objectives of sustainable development can be accomplished using the volatile organic compounds (VOC) produced as byproducts (Jung et al., 2010; Patel et al., 2019) [21,22]. There is a dearth of information regarding a viable and sustainable way of processing food waste, even though modern technologies are being adopted on a local or nationwide level in many developing nations. Finding a more environmentally friendly alternative technology for efficient waste-to-energy transformation is therefore urgently needed considering the depletion of fossil fuels and rising demand for green energy.

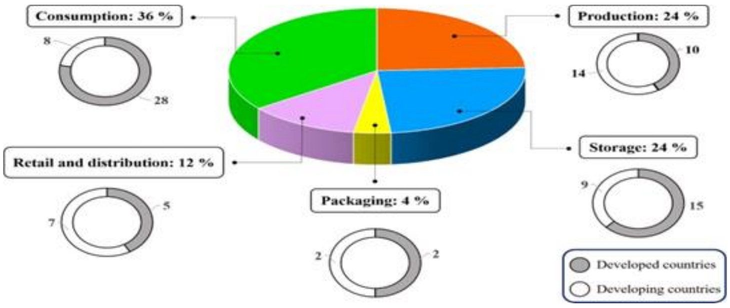


Figure 1: From manufacturing to consumption, there is a global distribution of food waste. The donut diagrams show how much food is wasted (in percentage) in both poor and developed nations along the whole value chain.(Sridhar et al., 2021)[5]

This research thus addresses the most modern methods for converting food waste into electrical power. Anaerobic digestion, pyrolysis, composting, landfills, incineration, and biochemical processes have all been studied, along with the advantages and disadvantages of each. Sustainable energy conversion technologies are attractive because they provide a viable approach to the sustainable management of food waste, particularly hydrothermal carbonization, and supercritical water gasification, have received significant attention. In addition, it has been suggested that a focus be placed on life cycle analysis, optimization with multiple goals, and the circular bioeconomy since these methods might be used as a new way to gauge the economic and environmental effects of various decisions. Finally, to foretell the future, the safety implications and potential futures have been offered. To turn food waste into useful energy, this endeavor would offer a comprehensive and sustainable strategy.

2. Review Methodology

A bibliometric study has been carried out for a more comprehensive evaluation to evaluate the potential and global interest in converting food waste into electricity. A useful method for assessing the growth and development of a particular research area is bibliometrics. To anticipate the variance in patterns, data is extracted and evaluated. Data for the last 10 years (2010-2021) of our study was taken from Scopus and obtained on April 15, 2021. (https://www.scopus.com/) The data was also mapped using VOSviewer software (Synnestvedt et al., 2005; Xie et al., 2020) [23,24]. The outcomes presented in our research were restricted to English-language literature from the engineering and sciences fields. Add "energy" OR "energy utilization" OR "biogas" OR "fuel" OR "biofuel" AND "food waste" OR "food residue" OR "kitchen waste" OR "household waste" OR "agricultural waste" as keywords to the search title. Add "energy" OR "energy utilization" OR "biogas" OR "fuel" OR "biofuel" AND "food waste" OR "food residue" OR "kitchen waste" OR "household waste" OR "agricultural waste" as keywords to the search title. Figure 2 shows a network analysis based on research done over the previous ten years (2010-2021) in various nations to comprehend the topic's worldwide reach. The number of research publications and global collaborations on the topic of turning food waste into energy from 2010 to 2021 is displayed by the cluster analysis. The weight of the aggregate is determined by the size of the circles, which is positively connected with the nation's citation count. The number of citations and research journals produced in a nation increases with the size of the circle's radius(Xie et al., 2020) [24]. Like how stronger co-authorship is proportional to how thick the connecting links between nations are. According to the cluster data, the United States (US) had the most research papers written by writers (161), China (147), India (123), and Malaysia (61) came next. With minimal information on energy conversion, most of the research published over the past 10 years on the topic of food waste have concentrated on food safety, leachate/pathogen removal, microbial community investigations, and life cycle assessments (Gao et al., 2019; Zhang et al., 2018) [25,26]. Thus, discussing the advancements and technology for turning food waste into energy is crucial.

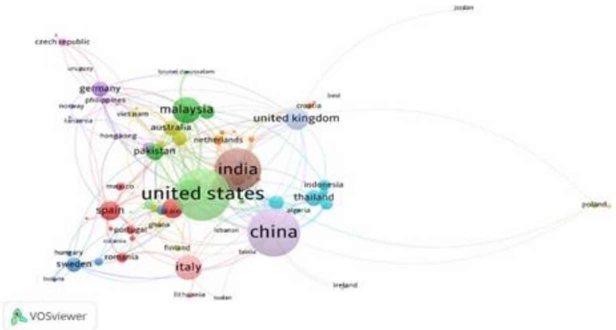


Figure 2: Bibliometric data illustrating an ensemble review of the nations that have published studies on the conversion of food waste-to-energy over the previous ten years (2010–2021), (Sridhar et al., 2021) [5]

3. Available Methods at the Moment how to Turn food Waste Energy

3.1 Incineration

One of the waste treatment methods with lower demands is incinerating waste(Mayer et al., 2019). It includes burning garbage to generate heat and energy. In process industries, the energy recovered might be utilized to power heat exchangers or turbines. The method can minimize the volume of solid trash delivered for disposal by 80–85% (Pham et al., 2015) [27]. Even though heating is one of the safer disposal methods, it is not a practical option because of the high emissions and air pollution caused by heavy metals. Ash, a result of incineration, also has to be properly disposed of since it includes inorganic waste. Municipal garbage and food waste were processed at temperatures around 850 and 1100 °C, according to a Korean study on energy recoveries. The results showed that 1 g of food waste had a carbon credit of 315 kg of CO2 and produced about 37.7 kJ of heat. While the results are promising, it should be noted that processing food waste alone will lead to higher energy loss due to organic waste (manure, fruit, and vegetable peels, etc.) (Kim et al., 2013) [28]. Second Swedish research found that even after segregation, 20 to 25 percent of municipal garbage was made up of food waste. These actions could have an effect on the economy, operational costs, and fuel quality (Svensson Myrin et al., 2014) [29]. Thus, it is reasonable to conclude that to improve the quality of the refuse-derived fuel part produced by incineration, appropriate residential waste separation should be completed before treatment.

3.2 Landfills

Landfill treatment is one of the most widely used methods of getting rid of all kinds of rubbish. Landfill gases (LFGs) are a significant human-caused methane source, contributing 8% of global emissions.

according to the United States Environmental Protection Agency (USEPA). By 2025, this percentage may rise. The shortage of usable land throughout the world is the biggest issue in treating waste. Over 12,500 tons of rubbish are transported daily by truck or train from populated places like New York to the surrounding regions (Palaniswamy et al., 2013)[30]. Several industrialized nations such as Canada has agreed to export 1.5 million tons of trash from Toronto to the United States annually (as a potential remedy) . Food and organic garbage make up the majority of trash in landfills, producing roughly 125 m3 of greenhouse gases, with 60-65% of these being CH4 and 40% being CO2 (Adhikari et al., 2006)[31]. The debris that is dumped in these waste dumps sits and forms piles over time, decomposing to create LFGs such CO2, methane, and other climate-changing gases. Landfills are a straightforward, cost-effective, easy, and convenient way to dispose of waste with less final product, but there are a few factors to consider. Landfill locations should be carefully chosen, distant from populated areas. The locations may serve as a haven for pests and insects like rodents and mosquitoes that spread diseases to people. Additionally, the methane oxidizes into CO2 and coats the soil over time. For example, Korea conducted research on the effects of methane formation from food waste leachate. According to the study, the maximum leachate biodegradability during a 30-day period was 64-69%, and the generation of CH4 ranged from 0.272 to 0.294 L/g (Behera et al., 2010) [32].

These leachates are self-generating, detrimental, and poisonous to the surrounding ecosystems as they seep into the soil and progressively release suspended chemicals, heavy metals, and macro components over time, contaminating the groundwater (Melikoglu et al., 2013; Shehzad et al., 2015) [[33,34]. Developing an effective leachate waste treatment strategy is the key problem. In addition to more conventional processes including precipitation, adsorption, and evaporation, research has also been done on advanced oxidation treatment employing ozone. The expected NH3-N removal rates were 72–96% with 0.60 kg O3/kg COD removal, according to the modeling findings (Abu Amr et al., 2013) [35]. Use of landfill-engineered reactors is another environmentally friendly processing method (Behera et al., 2010) [36]. These unique reactors function as bioreactors by recirculating leachate and adding moisture to treat liquid organic waste, producing the most energy with the least amount of facility use. When compared to standard landfill treatments, the rate of decomposition, cycling rates, and operating features have all shown to be effective (Benson et al., 2007; Khire & Mukherjee, 2007) [37,38]. Several models have been assessed to have been assessed in order to quantify the overall LFG content and comprehend the emissions brought on by food waste. Based on research conducted by Abu Amr et al. (2013) [35], commercial design and reaction optimization have utilized statistical techniques in addition to general mathematical models such as response surface methodology (RSM) and central composite design (CCD). However, these statistical techniques do not take into account variables like the waste's composition, the area's population, the age of the landfill, and the coefficient of methane correction. The IPCC technique, Tabasaran and Rettenberg first-order model, modified triangular model (MTM), first-order model, and landfill gas emission model (LandGEM) have all been proposed recently due to their promising potential for accurate methane emission from food waste. According to Ghanbarzadeh Lak et al. (2018), these advancements have resulted in a 25% drop in the demand for catalysts, a 25% gain in efficiency (removal of COD by up to 80% from baseline values), and a decrease in energy consumption. The models that have been used to regulate landfills in order to properly dispose of waste are listed in Table 1.

3.3 Putting up compost.

A variety of microorganisms are used in the biological process of composting to provide treatment. (Alta Tiquia, 2002) [39]. Enhancing the compost's or the finished product's nutritional content is the aim of introducing bacteria. By adjusting the conditions, food waste may likewise be converted into heat and energy using this procedure. Energy recovery rates were determined to be around 1895 kJ/hour for lab-scale systems, 20,035 kJ/hr for pilot-scale systems, and 2,04,907 kJ/hr for commercial systems in research on compost utilization employing food waste (Smith et al., 2015) [40]. The process of composting food waste to produce useful energy is shown in Figure 3. Several factors impact the composting process, including temperature, bulking agents, particle size, moisture content, microorganisms, and the combination of food waste added to the composting tank (Rastogi et al., 2020; Kausar et al., 2013, Mizan et al., 2024) [41,42,43]. Three phases may be used to describe them: the cooling or maturation phase, the thermophilic phase, and the mesophilic phase. Molds, yeasts, and mesophilic bacteria aid in the initiation and processing of organic materials during the mesophilic phase. For example, vegetable peels frequently require temperatures between 30 and 45 ◦C and a low pH of 4.5–5. Nonetheless, the temperature and pH gradually rise due to the breakdown phase (thermophilic phase) (Huebener et al., 1998) [44]. During the thermophilic phase, organic matter like lignin, hemicellulose, and lignocellulose is broken down with the help of certain bacteria and fungi. Temperatures in composting piles can rise to 80°C during this first stage of the composting process, which is favorable for the growth of bacteria (Bacillus species), fungus, nematodes, and protozoa (Santos et al., 2006)[45]. The last stage, known as the cooling or maturation phase, is when the overall level of microbial activity falls. When compost ultimately formed, food waste breaks down and releases heat and energy in the form of biofuels and useful energy resources. Aeration rate, temperature, pH, moisture content, C/N ratio, and stability of the resulting organic compost are evaluated (Palaniveloo et al., 2020) [46]. This organic matter, also known as compost, can be added to boost soil production. To create a safer compost, different composting techniques have been evaluated in relation to productivity, energy, and emissions. Table 2 discusses some of the most promising composting techniques, including windrow composting, in-vessel composting, vermicomposting, and static composting. Superior compost produces less ammonia, has a rich color, and smells well. In addition to these general characteristics, physical characteristics including density, enzyme activity, anion-cation exchange capacity, wetness, porosity, oxygen content, mass, and the amount of organic matter must also be considered when creating biodiesel or clean energy (Azim K et al., 2018). Compost soil microbial fuel cells, with urea acting as the compost and graphite acting as the functional electrode, have been used in recent research to assess fuel recovery. The results showed that 3.16 W/m2 of power density and 0.5 g/ml of concentration would be the ideal values for urea fuel cell performance, providing a starting point for the creation of technology to produce inexpensive and sustainable energy (Magotra VK et al., 2020) [47]. To find out more about utilizing microbial fuel cells and adding organic vermicompost matter to recover energy from food waste, an alternative, state-of-the-art study was evaluated. Nowadays, food waste can generate green power, also known as bioelectricity, because of the experiments' 0.41 mW maximum output and 0.75 V voltage (Youn S et al., 2015). Similar studies have also been conducted to produce bioelectricity using microbial fuel cells derived from plants, specifically rice plants (Moqsud MA et al., 2015) [48]. Hence, one way to start producing green energy from food waste is through effective fuel cell composting, even though these inventions are still in their infancy and only generate modest amounts of energy.

3.4 Anaerobic digestion

Regarding growing issues like waste management and climate change, anaerobic digestion is among the most promising methods. Biogas or methane can be produced with this method in thermophilic (60◦-80◦C), mesophilic (30◦C-50◦C), and psychrophilic (10◦C-20◦C) environments (Abdelsalam E et al., 2016). In comparison to aerobic digestion, it also provides higher loading rates and improved pathogen eradication, leading to an increased yield. Table 3 shows the steps involved in anaerobic digestion of food waste to create usable energy. Food waste can be turned into useful energy and is typically produced by farms, industry, homes, restaurants, and university canteens. The process of digestion can be broken down into four phases: methanogenesis (converting acetates to methane), the processes of hydrolysis (turning proteins into soluble sugars or fatty acids), acidogenesis (turning amino acids into intermediate fermentation products), and acetogenesis (converting high order fatty acids to acetate compounds and hydrogen) (Deepanraj B et al., 2018, Khalekuzzaman et al., 2023) [49,50]. In contrast to conventional methods such as incineration and landfill management, the waste management technique reduces carbon and greenhouse gas emissions by using less space and producing products with renewable energy (Khanal SK, 2006). The following equations (1) and (2) provide an explanation of the energy equations for temperature-based anaerobic digestion of food waste (Xiao B et al., 2018) [51]: $ns = \Delta E\ Vs*Q*Rs$ (2) $\Delta E = E0 - Ei$ (1) where Q is the food substrate flow rate (m3/s of reactor), Rs is the organic matter degradation rate (%), ΔE is the energy balance (kJ/d), and ns is the energy conversion efficiency. Vs is the degraded volatile solids (g of volatile solids/m3). The process of anaerobic digestion for turning food waste into products with additional value is shown in Figure 4. Numerous studies have been carried out to improve the process of anaerobic digestion. For example, a study examined the efficacy of treating food waste using a single-state and two-stage anaerobic digestion process with variations in ambient conditions. Due of the intricacy of the digestive process, this was done. The digesters that had one stage had a volatile solids destruction of 83.22 ± 1.33%, whereas the digesters that had two stages had a value of 82.02 ± 1.25%. Moreover, biogas yield average for two-stage systems was 0.810 ± 0.13 L/g, whereas yield average for single-stage systems was 0.775 ± 0.20 L/g (Xiao B et al., 2018). Similar research utilizing kinetic modeling methodologies showed that a two-stage anaerobic digester produced a 20% gain in energy output with 66.7% elimination of volatile compounds (Gioannis et al., 2017) [52]. In addition to process control improvements, a number of designs of experiment techniques, including artificial neural networks, Taguchi method, and response surface methodology (RSM), have also productivity. For example, the biogas performance from a jatropha plant was estimated using a Taguchi optimization model. The model demonstrated an overall increased efficiency of 1.11% 2% in contrast to the conventional thermodynamic model, and with just a little increase in temperature and pressure (Ganapathy T et al., 2009) [53]. Using food waste, Using Taguchi design and RSM, comparable multi-response optimization experiments were conducted, yielding optimal values of pH-7, temperature-50 ◦C, and C/N ratio of 20.19 (Deepanraj B et al., 2016) [54]. While there has been great progress in food waste anaerobic digestion, instability and procedure administration remain important considerations.

Table 1: lists the models used to govern landfills and ensure effective waste disposal.

Name of the model	**An explanation and its importance**	**Equations in mathematics**	**Utilization**	**Restrictions**	**Citations**
Model of Land Gas Emissions (LandGEM)	Based on US trash generation and climate, a model was run to assess the landfill's capability for producing CH4 (L0) and its coefficient of methane production rate (K). The availability of nutrients for organism reproduction, the proper pH, moisture content, and temperature of treated waste are some of the elements that affect the value of K. Based on the methane outputs of a certain waste component found in the software and literature, L0 is estimated.	QCH4 = ∑n i=0 ∑1 j=0.1K*L0* Mi 10*exp(−K*ti,j)Where QCH4 = Annual production of methane/year (m3 /year) i = time increment (per year) j = cutting the year in tenth n = difference between the year calculating and first year K is the methane generation coefficient (per year). L0 = Potential of CH4 production Mi = Mass of waste accepted (per year) ti,j = Age of waste	To evaluate the general solid waste's composition, a model is utilized.	Despite its well-known simplicity, this kind of model is only applicable to a single country and cannot differentiate between various waste kinds.	Gök and Fallahizadeh et al., 2019
Intergovernmental Panel on Climate Change (IPCC) model in many phases	The IPCC model is a multiphase model that enables global predictions of k values and LFG production. The model provides precise information on cellulose, lipids, protein degradation,	αt = c ∑0 i=1cAC0,ik1,ie − k1,it 1 Where αt = Landfill gas production at given time (m3 LFG/year) c = Dissimilation factor i = Waste fraction A = Amount of waste in the location C0 = Amount of organic matter in waste k1,i = Degradation rate constant t = time since depositing of waste (per year)	Studies on several categories, such as food waste, garden waste, paper waste, etc., may be evaluated using this model.	A landfill's age may be predicted, which would provide more accurate findings for better data modeling.	(Kraus et al., 2016; Banaget et al., 2020)

	and population in a given region while projecting methane generation for a single landfill. In contrast to the LandGEM model, the IPCC may forecast the software's default data or take site-specific composition data into account. Depending on whether a place has a tropical, dry, or rainy environment, the value of k can change. Food waste's k value typically ranges from 0.06/year (dry) to 0.4/year (wet and tropical).				
The triangular method modified (MTM)	dependable technique for calculating landfill-derived CH4 emissions. can be applied to waste conversion in the absence of sufficient data. The model is divided into two stages. The first stage begins with the start of gas generation and lasts for a year. Within three to six years, the second phase	G = 1.87MiWhere Mi = Mass of waste accepted in a year i G = Production	used when information on the composition of food waste is lacking	More attention may be paid to gathering information for precise methane recovery estimation.	(Das D et al., 2016)

	begins, during which the production rate is thought to peak and the creation of LFG declines to zero. Next, the total amount of gas produced is computed. The research of methane generation based on waste's biochemical breakdown is addressed by the multiphase model.	A= Total amount of garbage generated C0 is the amount of organic waste; k1 is the annual degradation rate constant, or 0.094. Time elapsed (t) = year	can be used to research how organic carbon breaks down in garbage.	When creating the model, landfill gas creation and recovery might be considered.	(Chakraborty M et al., 2015)
First order model		h the study of methane production based on biochemical decomposition of αt = c*1.87*A*C0*k1*e−k1 *t Where αt = Landfill gas production at given time (m3 LFG/year) c = Dissimilation factor, 0.58 The model makes the assumption that small variables like the amount of carbon left in landfills won't have a significant impact on the breakdown process or slow down the rate at which methane is produced. Due to its consideration of landfill age, the model is often favored.			
Rettenberg and Tabasaran's first-order model	A first-order model that helps explain the production of methane. The landfill conditions are assumed to be ideal by the model.	Gt = cCorininal(0.014T +0.28) (1 − 10− kt) MtWhere Gt = Landfill gas formation Coriginal = Initial organic carbon content (kg/ ton waste) T = Temperature t = Total length of landfill waste in that location	50% water content and 50% waste scrap are the ideal ratios for waste processing.	When modeling data, gas collection, well configuration, and leachate collection data must be taken into account. It is necessary to assess and	(Osin, 2006)

	(per year) k = first order rate constant (year− 1) Mt = Waste in place at time (t)		compare carbon credits with other environmental variables.	

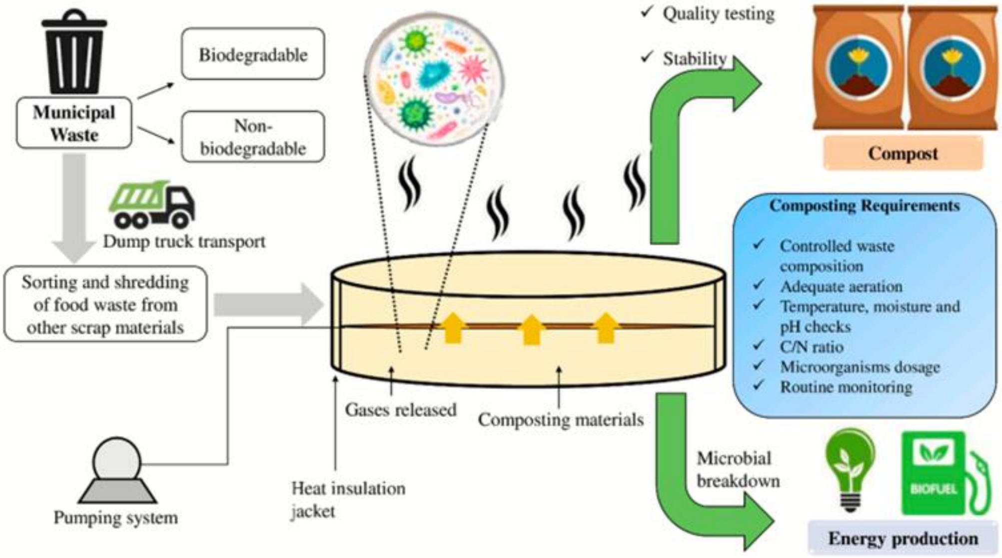


Figure 3: Utilization of food waste to valuable energy through composting

Table 2: lists the attributes of several composting methods for waste management.

The name of the method for composting	Procedure technology	Capacity for treating waste	Treatment difficulties	Compost production time and overall expense	Citations
Vermicomposting	Compost is produced by earthworm activity. Processing parameters including pH, moisture content, and temperature should be routinely monitored as earthworms are temperature-sensitive.	2–3 tons of waste	Changes in processing may affect earthworms. The ideal temperature range for earthworms and a successful vermicompost is 13 to 25 ◦C.	Low (approximately 2 months	(Ramnarain YI et al., 2018)
Windrow composting	Grease and manure in large quantities can be processed. The food waste is piled up or raked (either trapezoidally or triangle-shaped) and manually combined. A crucial factor in the process is temperature.	>10 tons	need vast land expanses and massive treatment equipment.	High	(Vigneswaran S et al., 2016)

Active aeration in static composting	Putting up compost that is quick and easy, using less time and space.	5–10 tons	The entire process's cost must be taken into account.	Duration: 2-4 months Expense- Medium	(Pergola M et al., 2018)
In-vessel composting	Able to handle a lot of rubbish in a little area. Food waste must be manually moved while it is full and allowed to air dry in designated containers. able to manage various waste types and has been used in industry.	1–5 tons	Trained workers are required to handle trash.	Duration: 12 days Cost: Minimal	(Makan A et al., 2019)

Table 3: lists the steps used to produce useful energy through the anaerobic digestion of food waste.

Phases of digestion	Responses	Conversion procedure	Citations
Hydrolysis	$(C_6H_{10}O_5)_n + {}_nH_2O \rightarrow n(C_6H_{12}O_6)$	Large protein molecules (starch, cellulose, sugars) are broken down with the help of anaerobic bacteria.	(Anukam A et ai., 2019)
Acidogenesis	$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$	fermentation inside the digester to create short acid chains.	(Deepanraj B et al., 2014)
Acetogenesis	$2CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + CO_2 + 3H_2$	The primary byproduct of fermentation is the conversion of volatile acids to acetates as a result of microbial reactions.	(Debruyn J et al., 2007)
Methanogenesis	$CH_3COOH \rightarrow CH_4 + CO_2$	methane production as the end result.	(Abbasi T et al., 2012)

3.5 Pyrolysis

Pyrolysis is a type of thermal breakdown that takes place in the absence of oxygen at temperatures higher than 300 °C. Following waste processing, the ultimate products recovered are gas, charcoal, and bio-oil. Due of the materials' numerous industrial applications and recyclable nature, interest in the technology has grown. Furthermore, the generated products (biochar) have been assessed for the elimination of dangerous contaminants found in wastewater (Muthamilselvi P et al., 2018). Moreover, biochar produced by fast pyrolysis could be used in agricultural, metallurgical applications, power generation, flue gas cleaning, and construction. Following flash pyrolysis, Bio-oil has been considered a fuel to feed ratio energy source. The biocrude produced can be utilized in turbines or engines in the automotive and aviation industries, or it can be recycled as feedstock (Demirbas A et al., 2001). It should be mentioned, nevertheless, that pre-treating food waste is necessary to prevent lowering the process's overall efficacy. Therefore, taking into account the economic and environmental aspects, food waste is combined with either biomass or chicken waste in an attempt to potentially address the issue. (Nizami AS et al., 2015; Hasan et al., 2023). Co-pyrolysis, catalytic pyrolysis, slow pyrolysis, and rapid pyrolysis are the four most often used pyrolysis techniques. Slow pyrolysis involves heating reactants slowly over extended residence times, whereas rapid pyrolysis uses faster heating rates and shorter reaction durations (>500 0C) to produce charcoal and bio-oil, respectively. Despite not producing any waxy chemicals, the products cannot be used directly as fuel for aircraft or other forms of transportation (Jeevahan J et ai., 2019). On the other hand, catalysis pyrolysis is preferable since it produces hydrogen-rich gas and better biooil quality when catalyst is added. (Kim S et al., 2020). Without changing the entire apparatus, pyrolysis can also be performed with two or more feedstocks to increase the output and quality of bio-oil (Park C et al., 2020). In Table 4, the features of several pyrolysis technology types are displayed together with how they are used to transform food waste to energy. An illustration of the pyrolysis process's mechanism, along with its end products and uses, is provided in Figure 5. The primary factors influencing the product yield are temperature, residence duration, and feedstock composition. The end result can be attained by adjusting any one of these parameters alone or in combination. One optimization research, for instance, was carried out by (Abnisa S et al., 2013) included pyrolyzing leftover polystyrene from palm shells in order to determine the yield. To determine the optimal conditions and the impact of various factors for achieving desired responses, the process was optimized through the application of response surface methodology (RSM). Similar investigations were carried out with coconut and rice husk waste (Isa KM et al., 2010). Research on adsorbents—materials that can absorb liquid or gaseous mixtures—that are produced during the pyrolysis of food waste items has been conducted recently. As an example, (Sim CK et al., 2015) focused on turning food waste into eco-green carbon, an activated carbon based on vermicompost. The favorable outcomes suggested their use as a material for the electrode in supercapacitors. Another study suggested using this kind of garbage as an inexpensive and effective adsorbent material (Modal S et al., 2015). By addressing the sustainability aspect of pyrolysis, these technologies increase its appeal for industrial applications. These factors lead us to believe that pyrolysis treatment holds greater promise than alternative approaches. n the context of economic analysis for food wastage systems, Rahman and Shohan's (2015) insights into supplier selection's impact on water treatment system equipment purchases can be adapted to explore analogous supplier dynamics within the food industry. Siddique et al.'s (2023) and Molla et al.'s (2023, 2024) considerations of cryptocurrency systems and medical textiles with plantable and implantable options, respectively, could be applied to evaluate innovative financial models and sustainable packaging materials in the food sector. Mustaquim's (2024) work on remote sensing methods in land surface interpretation can be leveraged for optimizing agricultural practices and supply chain management to reduce food waste. Noman et al.'s (2020) data retrieval approach may provide valuable insights into efficient data management for tracking and minimizing food wastage. Hasan et al.'s (2017) solar cap energy production system can be explored for renewable energy solutions in the food processing industry. Kamal et al.'s (2019) use of RFID technology for warehouse management offers a practical application for tracking food supply chains and managing inventory. Parvez et al.'s (2022) discussions on ergonomics factors can be employed to enhance the efficiency of workers in food processing units, ensuring a streamlined production process. Ullah et al.'s (2023, 2024) contributions on manufacturing excellence, operational scheduling, and equipment efficiency are pertinent for optimizing food production processes and minimizing wastage. Shakil et al.'s (2013) insights into process flow charts from a jute mill can inform methodologies for analyzing and improving the workflow in food processing units. The job shop production findings by Ullah et al. (2023) may be valuable for reducing wastage in the context of food processing. Overall, these diverse contributions from various research papers can provide a comprehensive foundation for economic analysis and optimization strategies in food wastage systems.

3.6 Biochemical conversion technology

Fuel is produced from food waste via biochemical treatments, which employ various microorganisms, cells, or enzymes. A particular microbe (bacteria, fungi, algae, or specialized enzyme) is added to the pretreatment food waste before it is processed, allowing breakdown to occur in the absence of oxygen. Being an environmentally friendly method, the process is unique. Fermentation of ethanol is one of the most often used biological processes (Ma Y et al., 2019). The metabolic process of ethanol production involves the breakdown of unique sugars through biochemical processes. Eqs. 3, 4, 5, 6, and 7 may be used to explain the following processes and reactions that make up the cell culture mechanism. (Walker K et al., 2013): glucose and fructose are produced during the process of hydrolyzation, which uses sugar as the bio feedstock; Carbon dioxide and ethanol are produced during fermentation, which releases energy from glucose and fructose. separation, whereby the produced bioethanol is isolated from its byproducts via distillation. Anhydrous bioethanol is a renewable fuel that may be utilized, can also be produced via fermentation treated with additional organisms such as bacteria or fungi, or by continuing the enzymatic hydrolysis process (Khalekuzzaman et al., 2024). Figure 6, which illustrates the biochemical conversion of food waste to bioethanol, highlights the ethanol fermentation process using common bacteria, yeast, enzymes, and algae (Pandey BK et al., 2018). In the automotive sector, this fuel may be utilized straight to power gas engines and heat sources (Beyene HD et al., 2018).

$CH_3COOH + 2H_2O \rightarrow C_6H_{12}O_6 + CO_2 + 4H_2$ (3) $CO_2 + 2H_2 + CH_3CH_2CH_2COOH \rightarrow C_6H_{12}O_6$ (4) $H_2O + CH_3CH_2CH_2COOH + C_6H_{12}O_6 + 2H_2$ (5) $+ 2H_2 \rightarrow COOHCH_2CH_2OCOOH + CO_2$ (6) (7) $C_6H_{12}O_6 \rightarrow CH_3CH_2OH + CO_2$ In order to reduce the use of fossil fuels and create a hybrid fuel for commercial use, bioethanol is being combined with traditional fuels like gasoline more and more in the recent past. In countries like the US and China, a combination of maize and sugar crops is utilized as a feed source for the manufacturing of bioethanol. (Jiao J et al., 2019). The overall preference for feedstocks is food waste that is high in proteins, carbs, and cellulose materials. A novel strategy for producing bioethanol from pre-treated food waste has also been documented in recent years: the use of fungal mash (Ma Y et al., 2017). A bioethanol content of 71.8 g/L resulted in a 90% reduction in waste volume. Comparable studies with biomass and green algae (Chlorella pyrenoidosa) were carried out (Pleissner D et al., 2013). It should be highlighted, nonetheless, that larger bioethanol concentrations necessitate more purifying processes (distillation), which presents a problem for business scale-up. The entire procedure is also thought to be capital- and energy-intensive. Therefore, in order to improve food waste management, it is necessary to comprehend issues like process optimization, appropriate fermentation, and cost. It might be argued that food waste, which makes up a significant portion of municipal garbage, represents an underutilized potential for energy generation. Even if the present technologies have undergone thorough analysis, a number of factors still need to be considered, including robustness, environmental friendliness, waste composition, economics, scale-up, and impact on health.

Ecological ways to Convert Waste Into Energy

The need for environmentally friendly technologies that not only consume less resources but also yield better outcomes has increased over the past 10 years, but also concentrate on the techno-economic elements of processes (Ma Y et al., 2019). Currently, the creation of syngas and green energy from food waste through hydrothermal carbonization and supercritical water gasification has shown promise. Reaction parameters including feedstock composition, temperature, pressure, catalyst dose, and the ratio of biomass to water are critical for achieving high gas conversion (Su W et al., 2020). These procedures also enable superior heat recovery and take less time, opening the door for commercial use (Yan M et al., 2018). These were covered in the section below:

4.1 Hydrothermal carbonization

Hydrothermal carbonization (HTC) is a thermochemical conversion process that converts wet biomass or feedstock without the requirement for a pre-treatment step into solid (hydrochar), liquid (oils after extraction), or gaseous products. This happens much below 350 ◦C and with very little energy use. The water content of food waste can be used as a solvent in the HTC procedure.

Table 4: Features of several pyrolysis technology types for efficient food waste to energy conversion

Kind of pyrolysis	**Principal characteristics**	**Conditions of temperature**	**significant product created**	**Current events kind of waste**	**Conclusions**	**References**
Gradual pyrolysis	Over time, the temperature gradually rises.	400 ◦C – 500 ◦C	Charcoal	Litter for poultry (400–800 ◦C with nitrogen flow)	The obtained energy content was 1688. kJ/kg for gradual burning up to 550 degrees Celsius.	(Azizi K et al., 2017)
	Waste heats at a slow pace (approximately 1 °C per second).			Waste banana peel	Following the RSM investigation, 362 ◦C, 989.9 g of waste, and 104.2 min of time were ideal for achieving a	(Omulo G et al., 2019)

	Catalyst addition and temperature control are essential to this process.				48.01% yield. A 90% energy conversion efficiency was attained.	
Quick pyrolysis	Temperature increases significantly with a high pace of heating. Greater heat transmission occurs with a shorter residence period. Catalysts for Ni, Cu, or Fe added raises the output of bio-oil by 0.7-8.	600 ◦C – 1000 ◦C	Bio-oil	Litter for poultry	With an increase in temperature, the carbon content of biochar rose from 47 to 48.5%. The bio-oil output attained a weight percentage of 27% and a heating value of 32.17 MJ/kg.	(Campanella A et al., 2012)
				Millet pearls with Sida cordifolia L.	For pearl millet, the maximum bio-oil output was 48.27%, while for Sida cordifolia L., it was 48%. For both biomasses, the ideal parameters following RSM were 400 ◦C, 1.5 mm particle size, and 200 mL/min.	(Boubacar Z et al., 2020)
Pyrolysis via catalysis	The overall quality of the product is improved by the application of catalyst, resulting in less acidic and more stable oil. Apart from other catalysts like Ce, Zeolite, Mg, and Al, nickel-based catalysts are typically utilized for treatment	300 ◦C – 600 ◦C	Depending on the catalyst, composition, and temperature settings, biochar and bio-oil	Waste biomass	A 1:4 catalyst combination (ZSM-5 and CaO) produced 36% weight aromatic hydrocarbons.	L. Y. Jia et al., 2017)
				Wasted tomatoes	Using Cu/Al2O3 as a catalyst, the ideal temperature was 500 ◦C with a heating rate of 100 ◦C/min.	(Ozbay N et al., 2017)

	processes.			Kitchen waste	Using CaO catalyst, an acid reduction of 85.9% was accomplished. Using CaO as a catalyst and blending 50% kitchen trash and Chlorella vulgaris is thought to be the best possible treatment.	(Chen L et al., 2018)
Pyrolysis aided by microwaves	using microwave radiation to pyrolyze trash and produce biochar or biooil.	400 ◦C – 800 ◦C	Syngas, bio-oil	Food waste (vegetable leaves, white rice, meat)	A greater biogas production of 67.90% was obtained with an increased microwave power of 1400 W, which was 44.13% higher than the biogas preserved in nitrogen environment.	(Chen L et al., 2019)
The process of hydropyrolysis Hydropyrolysi	pyrolysis with hydrogen rather than nitrogen to enhance the quality of the liquid output.	300 ◦C – 450 ◦C	Bio-oil	Waste biomass	Hydrogen presence increased the quality of the finished product and the conversion of biomass.	(Lin J et al., 2020)
In tandem with pyrolysis	Pyrolysis that involves the use of two or more feedstock materials (such as wood bark and food scraps).	300 ◦C-700 ◦C	Biochar, polycyclic aromatic hydrocarbons (PAHs), and non-condensable gases (H2)	Plastic waste and soy protein	Reaction rates were 12–16% higher and activation energy was 2–13% lower for decomposition	(Tang Y et al., 2018)

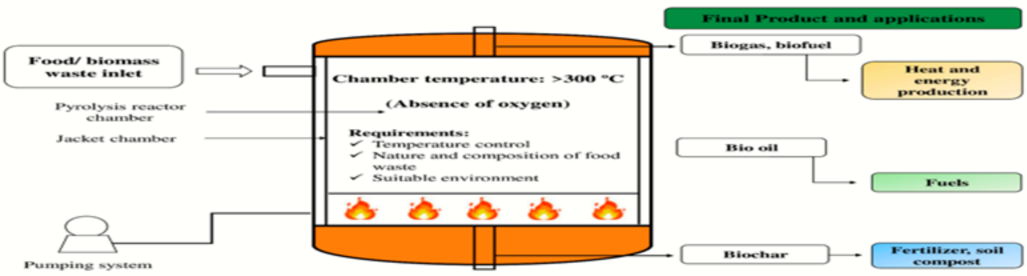


Fig. 5. Mechanism of pyrolysis process with their final products and applications.

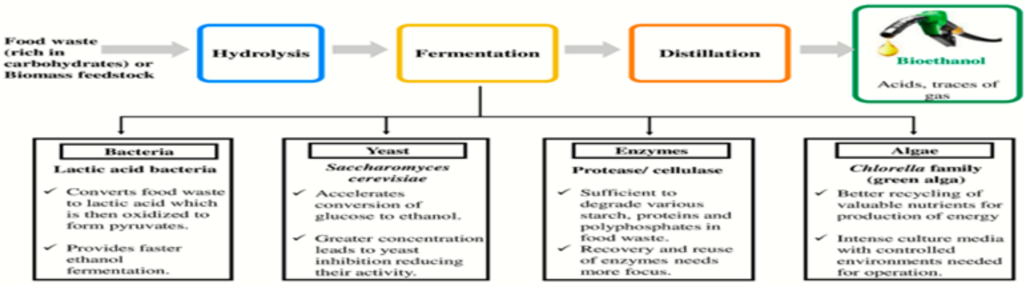


Figure 4: biochemical fermentation of ethanol utilizing ordinary bacteria, yeast, enzymes, and algae, with an emphasis on the conversion of food waste to bioethanol.

4.2. Gasification of supercritical water

Wet biomass is converted into hydrogen-rich syngas by the supercritical water gasification (SCWG) process. This is not like a traditional gasification process since it occurs at high pressure and low temperature (Kruse A, 2008). Furthermore, the technique uses very little energy during feedstock drying and pre-treatment (Chen J et al., 2019). A crucial component of the entire water-gas shift reaction is water. The concurrent reactions provided by Eqs. (8)–(11) can be used to understand the trash treatment process (Chowdhury MBI et al., 2017) in the following way.

Gas conversion: Eighth: $C_6H_{12}O_6 + H_2O \rightarrow 3CO + H_2 + 2CH_4$. Gas shift reaction in water: $CO + H_2O \downarrow CO_2 + H_2$ (9) Carbon + $3H_2 \downarrow CH_4 + H_2O$ is methanation (10) $CH_4 + 2H_2O + CO + 4H_2$ (11) The SCWG food waste treatment equipment is shown in Figure 8. Due to the technology's ability to manufacture syngas from wet feedstock in an energy-efficient manner, interest in it has grown. The optimal feedstock for this strategy is food and biomass because of their high moisture content (80–90%) and low salt content (1%).

Water is important to the process because of its many characteristics, such as its high diffusivity, low dielectric constant, and low viscosity. Moreover, it promotes more efficient hydrolyzation to provide gaseous byproducts.

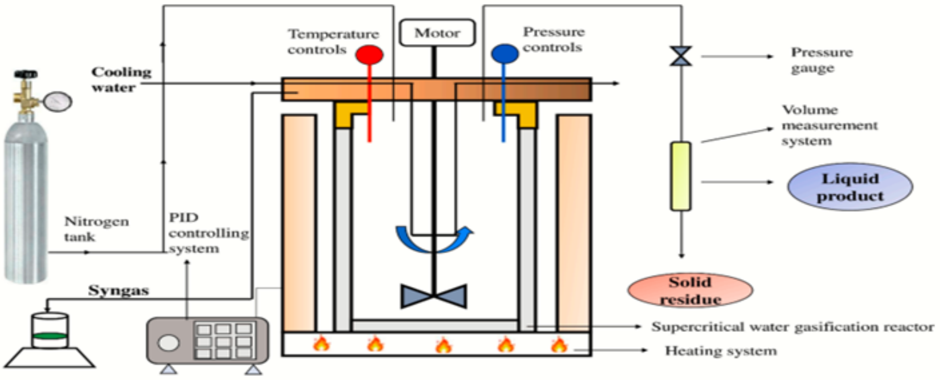


Figure 5: Equipment for supercritical water gasification is used to handle food waste.

5. Analysis of the Life Cycle

Life cycle assessment, or LCA, is a quantitative technique for assessing the potential environmental impact of a certain activity. The evaluation has a lot of potential to not only enhance the process's planning phase but also to inspire scholars to reconsider a number of laws and policies (Hetherington AC et al., 2014). In addition, compared to primary and secondary research methodologies, it provides a more accurate, expedient, and quantitative approach to performance assessment (Gloria TP et al., 2007) Mathematical weights are used in the analysis to improve decision-making. The steps involved in carrying out a life cycle assessment are shown in Fig. 9. A typical waste treatment life cycle analysis, as defined by ISO 14040, include life cycle impact assessment (LCIA), aim and scope, life cycle inventory (LCI), and result interpretation (Azapagic A and Clift R, 1999). The following describes each phase's specific purpose:

5.1. Phase 1: Objective and extent

During this process, the investigation's objective and scope are evaluated. To carry out a quantitative investigation, the functional unit is specified. The purpose of the functional unit is to compare the treatment's cost, energy consumption, transportation, and product recovery with those of other waste management treatments. One study carried out in China, for instance, treated one ton of food waste before it was introduced into the system. Evaluation criteria were taken into account, including location, fuel production, electricity generation, and pollution discharge. The biogas digester's energy consumption was 663.89 MJ, which increased the net energy value by 38% (Jin Y et al., 1015).

5.2. Life cycle inventory (LCI) in Phase Two

Compiling relevant data on labor, time, emissions into the environment, contaminants, energy utilized in manufacturing, etc. is a necessary part of LCI. According to Ahmed A et al. (2016), the data may be obtained by an on-site examination, acquired from official sources, or completed using LCA software like Simapro

Fig. 9. Phases for conducting life cycle assessment.

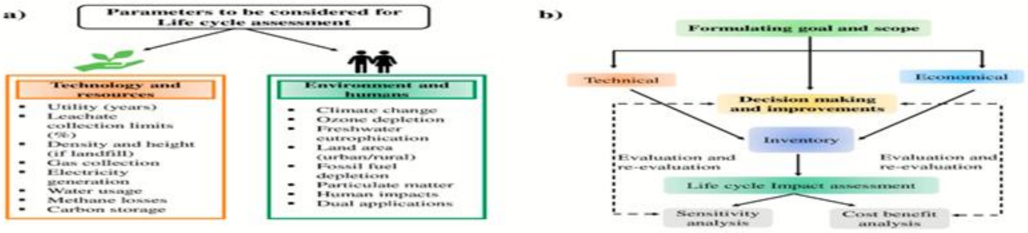


Figure 6: (a) The life cycle assessment procedure is carried out with consideration of the following parameters: (b) an overview of the process flow

5.3. Life cycle impact assessment (LCIA), Phase 3

LCIA includes quantitative weighing and characterization procedures. Different causes, calculations, and impacts result in different methods. For instance, two assessment techniques—Ecoindicator 99 and ReCiPe—were examined in a study on solid waste incineration in Taiwan. In both approaches, it was discovered that the most sensitive parameters were CO_2 emissions and electricity use. In conclusion, the weighted values for the ReCiPe technique ranged between 45.03 and 47.47 per kilogram of trash burned, while the Eco-indicator 99 ranged between 17.91 and 23.35 per kg of waste incinerated. The viability of both approaches in terms of resource conservation, environmental integrity, and human health was further demonstrated by sensitivity and improvement analysis (Ning et al., 2013). Figure 9(a) displays the parameters taken into account while doing a life cycle assessment, and Figure 9(b) provides an overview of the process flow during the evaluation (Lam CM et al., 2018). An overview of the crucial characteristics selected to comprehend the impact assessment of food waste is shown below Eqs (12),13 and 14:

1) CH_4 generation

CH_4 generated = DOCt × F × 16 12 (12) where F is the correction factor, which varies depending on the sort of procedure used, and DOCt is the degradable organic carbon. According to the IPCC panel, a correction factor of 0.4 is often selected as the default (Parra-Orobio BA et al., 2020).

2) Organic matter and other gases (for a specific year)

$DDOCm = W \times DOC \times DOCf \times MCF$ (13)

where, in accordance with IPCC (1996 recommendations), MCF is the CH4 correction factor = 0.5, DDOCm is the degradable organic matter deposited (Gg), W is the waste deposited (Gg), DOC is the proportion of degradable organic carbon, and DOCf is the decomposable fraction of waste (W. A. Qazi, 2021).

3) Transport emissions

$Emissions(tons/day) = E \times F \times t$ (14)

where t is the travel activity (kilometers per day), F is the correction factor, and E is the emission factor.

5.4. Phase Four: Analysis

Phase 1 involves verifying and assessing the inferred results from the inventory and impact assessment to ensure that they align with the purpose and scope. Sensitivity and cost-benefit analyses are performed to assess this stage and determine how robust the entire procedure is.

5.5 Analysis of cost and benefit

In order to assess the sustainability factor for efficient food waste to energy management, three important aspects are considered.: social, environmental, and economic issues. The life cycle's total cost and benefit (Lam CM et al., 2018) Analysis is provided by Equations (15) and (16). Cecon + Cenv + Csoc = Totalcost (15) Becon + Benv + Bsoc = Totalbenefit (16) Whereas Becon represents the economic advantages, Benv represents the advantages to the environment, Bsoc the social benefits, and Cecon the costs to the economy, Csoc stands for the social expenses, and Cenv for the environmental costs. Depending on national laws, the discounts vary from nation to nation. Furthermore, the values aid in the comprehension of the techno-economic facets of energy production. The costs of capital and operations are also included in the economic costs. This covers the expense of equipment, maintenance, la bour, power supply, and operation to process the food waste. Equations (17) and (18) provide a mathematical definition for this (Woon KS et al., 2016) P (1 + i) n (17) = F CAPannualized is equal to CAP plus i 1 − (1 − i) − n (18). where P is the current worth, CAP is the future worth, and F isThe initial capital cost (CAP), the yearly capital cost (annualized), the number of years (n), and the government-approved discount rate (i) are all given. Together with the conversion cost, consideration should be given to the initial waste composition, pre-treatment costs, and nutritional content of the input food waste, as these may vary. Furthermore, for a precise cost-benefit analysis, environmental advantages such as utilities, power grid, and pollution costs must be equally considered (based on geographic location). In addition, eco-nomics can be used in conjunction with the dual use of value products (bio-based products) for a variety of applications, such as bioplastics or biofertilizers. Thus, in addition to a potential societal approval survey carried out by, testing the end-of-waste status from the resulting products (Moretto G. et al., 2020). Calculating amenity cost and social benefits is necessary to take into account land utilization in highly populated areas across the globe. Prices for commercial areas or pilot plants in a certain area are examples of amenity costs, and these might vary from nation to nation (Woon KS et al., 2016). Value chain management, societal ties, and stakeholder transparency are all necessary for effective land exploitation (Lu YT et al., 2016). A 5.2% reduction is typically implemented for distances greater than 4.8–5.5 km from urban services, while local variations exist.

5.6. Analysis of sensitivity

Sensitivity analysis is a tool used to investigate issues related to uncertainty in order to enhance and make better judgments. Either an actual situation (case study for a specific site) or a set of parameters are used for the analysis. While adding a full list of quantification of uncertainties is recommended by international guidelines, according to (Hauschild MZ et al., 2013), Roughly 29% of instances included sensitivity analysis on specific parameters, 41% examined a case study based on its location, and 46% of cases excluded any mistake evaluations. Finding the mistakes and establishing the reliability of the mathematical models are the usual goals of the evaluation. The most sensitive parameter to the scenario and uncertainties is found by a robustness analysis of the LCA data. A 10% sensitivity is typically provided for each parameter chosen for investigation in order to conduct a systematic assessment of the sensitivity analysis (Ning SK et al.,2012). The most popular techniques for figuring out how sensitive a system is are scatter plots, response surface methodology, Monte Carlo simulation, analysis of variance, and regression analysis. Measuring the non-sensitive research parameters to make the model simpler is another method of assessing the sensitivity analysis (called factor-fixing) (Saltelli A et al., 2007). In light of this, we can say that LCA is a useful technique for comprehending the handling, processing, and decision-making of food waste. Results from cost-benefit and sensitivity analyses, however, may only be understood as an essential tool for understanding and estimating future values. Additionally, it is critical to give special consideration to a number of factors, including resource depletion, plant capacity, emission controls, and human consent. It is imperative that these techniques be followed in accordance with government regulations and that the number of emissions be reduced in order to improve management tactics.

6. Future Directions

Under the current circumstances, more work will be needed to achieve the Sustainable Development Goals in the field of converting food waste to energy. The future lies in focusing more on the most effective solution for handling food waste. Figure 10 shows the future of sustainable food waste to energy management. The following future thoughts on efficient food waste to energy management are informed by the author's knowledge and research.

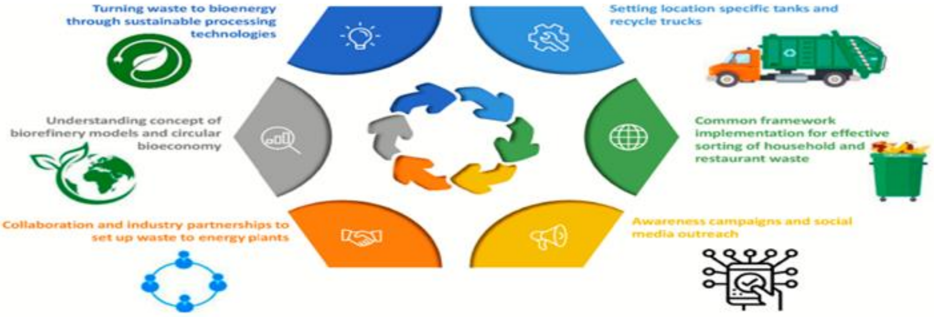


Figure 7: Future directions for efficient energy management solutions involving food waste.

- The advancement of innovative methods to transform food waste into valuable resources such as biofuels, biodiesel, hydrochar, syngas, and biogas for industrial use.
- Combining data-driven technologies like artificial neural networks and machine learning (ML) with food waste management could be one of the most exciting future directions in the field. This could lead to improved process optimization, higher rates of recyclability, and better final product quality (Gonçalves Neto J et al., 2020). An alternative method of quantifying data may be to use a common waste collection facility or a standard structure with frequent checks. A potential route for integrating data-driven technologies to improve pattern identification and decision-making is shown in Figure 10. It is simpler to evaluate, contrast, and benchmark findings when baselines and standards are established at every level. This might aid in closing the skill gap in problem-solving.
- Reducing trash at the source should be done in a sustainable manner. Crop residue burning can be reduced, for instance, by using agricultural waste produced during post-harvest treatments to generate electricity (Sharma S et al., 2020). Reducing the belief that trash belongs in landfills and educating people about the advantages of energy production will help address problems like pollution, global warming, and climate change.
- Those that do adhere to food waste separation guidelines ought to face harsh penalties
- Information on efficient food waste to energy conversion should be made available by NGOs, awareness campaigns, and social media campaigns. The usage of biogas, biofuels, bio-oils, and biofertilizers should also be promoted.
- According to Mu'azu ND et al. (2019), there isn't a strategy, plan, or forthcoming initiative for effectively managing food waste. Therefore, a clear policy or possible future course should be defined for improved decision making. The Indian government and National Thermal Power Corporation

started the "waste to energy mission" a few years ago with the goal of installing 5 million home biogas plants in an attempt to reduce the quantity of fossil fuels consumed in the production of electricity (Bhuvaneshwari S et al., 2019). While other poor nations are gradually acknowledging similar efforts, further support is required to accomplish sustainable organic waste management.

- Finally, because of an imbalance in the supply chain, the COVID-19 pandemic has resulted in a rise in food shortages and waste (Sharma HB et al., 2020). Therefore, in order to achieve a circular economy, emphasis should be placed on lowering the quantity of food waste, improving nutrient recycling techniques, and adhering to the idea of zero waste discharge.

Figure 8: Potential future direction: merging data-driven technology to identify patterns and make decisions.

7. Conclusion

For food waste management to be successful, three factors have to be carefully considered: energy, environment, and economy. The academic community and experts in the industry have been interested in the expanding movement to turn trash, particularly food waste, into valuable energy sources. The technologies used today for waste management are initially covered in this study, with a focus on landfills, pyrolysis, anaerobic digestion, composting, and biochemical techniques. Sustainable methods, which are frequently disregarded, must be used to safeguard the environment. In light of this, the evaluation emphasizes sustainable methods such as supercritical water gasification and hydrothermal carbonization, which have an advantage in terms of Price, quality of the product, and overall effectiveness. In order to demonstrate a viable method for making wise decisions, the study also examines the ideas of life cycle analysis and multi-objective planning, and bioeconomy models. Furthermore, safety considerations and recommendations for future advancements in technology related to the production of green energy and resource use have been mentioned.

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