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Recent Advances in Food Waste Conversion Technologies#

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ABSTRACT

Access to timely, affordable, and good quality food is a sine qua non for human existence. Unfortunately, huge volumes of edible foods are wasted or lost along the food value chain thereby impacting food security. Recycling and conversion of food waste ensure the appropriate utilization of the untapped resources in food waste. The current study reviews the biological (landfill, composting, anaerobic digestion, and fermentation) and thermochemical (incineration, pyrolysis, gasification, and hydrothermal carbonization) technologies for the conversion of food waste into clean energy, chemicals, and other utilizable products. The process, products, benefits, and drawbacks of these conversion technologies are also discussed. Commissioning of multidisciplinary and collaborative research is recommended to garner expert perspectives towards achieving cost-effective, ecofriendly, sustainable, and practicable food waste conversion technologies.

Keywords: food waste, leftover foods, conversion technologies, clean energy, biofuel

1. INTRODUCTION

Food is one of the essentials of life. One of the metrics for measuring the quality of life is access to quality, timely, and affordable food. The United Nations' (UN) Sustainable Development Goal (SDG) no. 2 is to end extreme hunger, achieve food security, and improve nutrition. SDG goal 12.3 also hopes to reduce global food waste by half by 2030 [1]. Consumption of nutritious food ensures healthy lives and promotes the well-being of the global population to contribute to economic development. One of the obstacles to food availability and accessibility is the menace of food waste. Food waste refers to edible food that is suitable for consumption but deliberately thrown away or discarded. Food waste also includes uneaten, leftovers, and spoilt food, fruits, and vegetables that are withdrawn from the human food supply chain. Waste food is also generated by households (kitchen), commercial setups (markets, supermarkets, canteens, restaurants, farms), and food processing industries.

According to the Global food waste statistics about a third of the edible food produced worldwide, amounting to about 1.3 billion tons, is lost or wasted yearly [2]. The household sector is the largest contributor to food waste with fresh fruits and vegetables as the most wasted food. China, India, and Nigeria are the leading producer of food waste globally, generating 91.6 million tons, 68.8 million tons, and 37.9 million tons per year from households (Figure 1) [3].

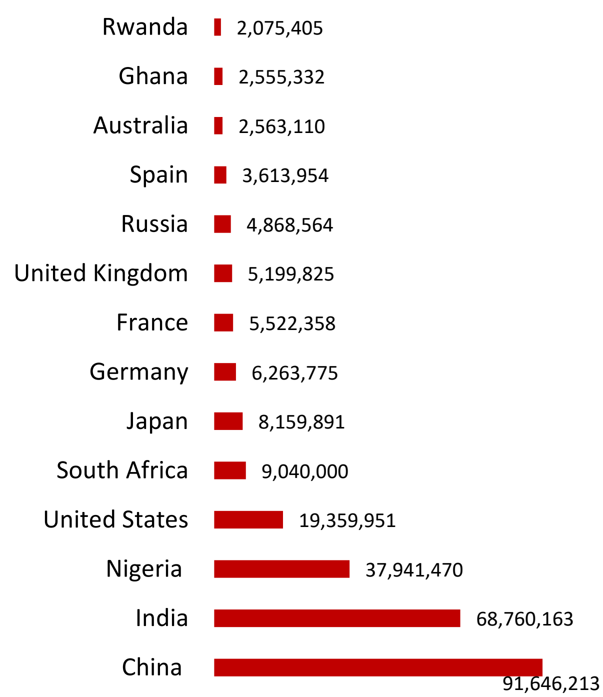

Fig. 1 Annual food waste generated by households in selected countries

Waste food has significant social, environmental, and economic impacts on humans. Available information reveals that wasted or unconsumed food exacerbates global warming and contributes 8-10 % of the total greenhouse gas emissions, globally. Reducing the quantity of wasted waste in the household and commercial sectors saves money, prevents odour and disease-causing bacteria, conserves energy and water, minimizes methane emission from landfills, and reduces the carbon footprint.

One of the strategies aimed at combating the menace of food waste is the conversion of unconsumed and discarded food items into usable products. In recent research, Mohanty et al. [4], Jung et al. [5], and Kazemi et al. [6] studied the conversion of wasted food to bioenergy, biodiesel, and bioethanol respectively. Chhandama et al. [7], Sharma et al. [8], and Mahssin et al. [9] also posited that food waste can be converted to biogas, biohydrogen, biofertilizer, bioplastics, asphalt binder, and other bioactive compounds. These authors agree that the conversion of food waste can improve sanitation, mitigate environmental pollution, and contribute to achieving a circular bioeconomy.

Despite these researches, the pertinent question to pose which forms the motivation for the current study is whether enough research has been carried out on food waste conversion. The aim of the current intervention, therefore, is to assess some of the technologies for the conversion of food waste into utilizable products. The outcome of this investigation will enrich scholarship by updating the available information on various pathways for utilizing food waste. This intervention highlights the benefits and drawbacks of some food waste conversion technologies and proffers the sustainable and innovative pathways to improving the quality of the products. However, this study is limited to a desktop review of the conversion of food waste relying on the information sourced from published peer-reviewed journals on the subject.

2. CLASSIFICATION AND COMPOSITION OF FOOD WASTE

There are no well-defined benchmarks for the classification of food waste, various jurisdictions classify food waste based on various criteria, including source, edibility, and status of consumption. Edible food waste can be waste generated food generated from fruits and vegetables, processed foods, leftovers, liquids, oils, and grease, dairy and eggs, meat and fish, baked foods, snacks and condiments, dry foods, etc. Table 1 major classification of food waste and its examples.

Edible food constitutes about 57 % of food waste while inedible food waste accounts for about 32 %. The remaining 17 % are questionably edible food waste. Conversely, edible food waste comprises fruits and vegetables, prepare food and liquid, oil and grease which account for 39 %, 28 %, and 9 % respectively (Figure 2) [10].

Just as the sources of food waste differ and their examples diverse, the composition of food waste varies widely according to the source, types, jurisdiction, time of the year, economic, and cultural persuasions. Generally, food waste can be characterized to determine the contents of its organic components. The composition of lipids, protein, carbohydrates, total solids (TS) and volatile solids (VS), carbon content, nitrogen content, and C/N ratio is needed to be able to determine their potential utilization options. Table 2 shows the characteristics and composition of some food waste [11].

Table 1. Classification and examples of food waste

Criteria	Classifications	Description	Examples
Source	Pre-consumption	generated during production and preparation	Peels, eggshells, coffee grounds, apple cores
	Post-consumption	consist of unconsumed processed or cooked food	Bones, leftovers
Edibility	Edible	Generated from mostly consumed foods	Fruits and food leftovers
	Inedible	Waste generated from typically unconsumed foods	Eggshells, plantain peels, banana peels, chicken feathers
	Questionably edible	Generated from not commonly eaten food	Potato peels, beet greens, carrot peels
Status of consumption	Pre-consumption	Waste generated before consumption	Eggshells, peels,
	Post-consumption	Waste generated after consuming the edible part	Bones, leftovers,

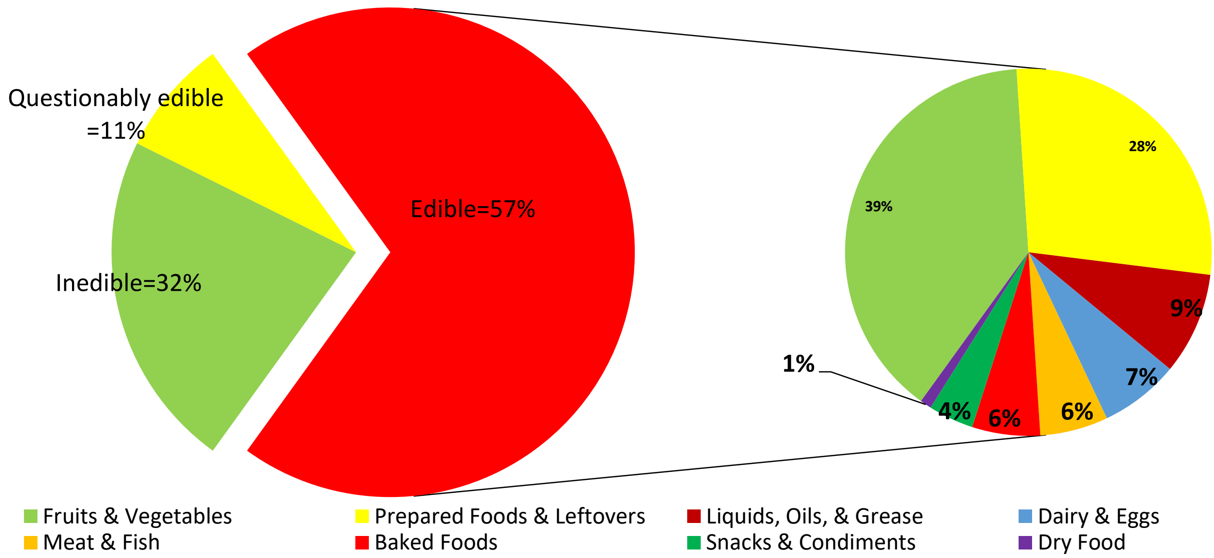

Fig. 2 Categories of food waste

The oil/lipids content of waste fruits and vegetables is lower than that of kitchen waste. Food waste containing carbohydrates and proteins in high percentages but low in oil/lipids are potential candidates for biogas synthesis while those with high oil/lipids concentration are easily converted to biodiesel [7].

Table 2. Composition of some food wastes

Characteristics	Kitchen waste	Leftovers	Fruits and vegetables
Protein, %	15	18.2	26.6
Lipids, %	23.9	20	35
Carbohydrate, %	55.2	29.4	32.5
TS, %	24	-	-
VS, %	23.2	90.8	29.3
C, %	54	50	48.4
N, %	2.4	2.8	3.8
C/N ratio	22.5	17.85	12.7
Na, g/Kg	7.26	7.38	10.1
Ca, g/Kg	5.42	9.49	1.7
K, g/Kg	46.94	36.35	9.6
Mg, g/Kg	21.14	20.94	0.7
Fe, g/Kg	2.41	2.92	0.041

3. TECHNOLOGIES FOR FOOD WASTE CONVERSION

Food waste accounts for about 50 % of the global municipal solid waste with roughly 931 million metric tons of food waste generated in 2019 [12]. China and India are the most producers of food waste, globally. The generation of food waste is projected to continue to escalate for the foreseeable future mainly in the Asian countries. The major stimulating factor for this trend is the unrelenting population growth. There are two technologies commonly deployed for the conversion of food waste into various products. The biological technologies comprise landfill, composting, anaerobic digestion, and fermentation while incineration, pyrolysis, gasification, and hydrothermal oxidation, as shown in Figure 3. Table 3 summarizes the advantages, disadvantages, conversion technologies, and products derivable from the conversion of various food waste.

3.1 *Landfills*

The landfill is believed to be one of the easy, economical, and convenient strategies for food waste conversion. About 50 % of the waste in landfills is food waste. Food leftovers, uncooked food items, packaged food, and uneaten fruits and vegetables from households, restaurants, and commercial establishments are disposed into landfills. Food wastes dumped in landfills form heaps of waste and are decomposed and converted into 60–65 % of methane (CH_4), 40 % of carbon dioxide (CO_2), and ammonia (NH_3) [13]. However, lack of land, the release of offensive odour, a breeding ground for insects and pests, generation of toxic leachate, and emission of anthropogenic gases continue to be some of the drawbacks of the landfill technique.

3.2 Composting

Composting is a viable biochemical process and has become a proven technology for the conversion of food waste into biofuel, fertilizer and other useful products. The process takes place in three successive stages. In the first stage, called the mesophilic phase, the organic materials in food waste such as uneaten fruits, fruits peels, vegetables, and leftover foods, at low pH (4.5–5) and temperature (30 and 45 °C), are processed by mesophilic yeasts, molds, and bacteria.

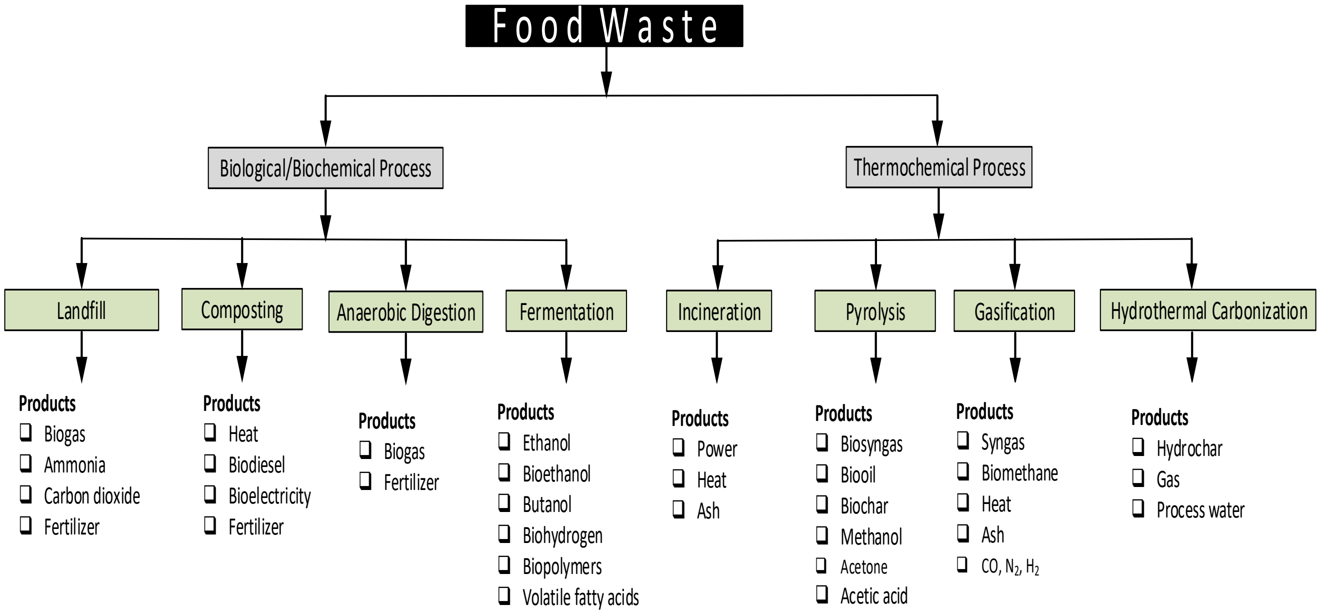

Fig. 3 Conversion technologies for food waste

In the thermophilic phase, the lignin, lignocellulose, or hemicellulose in the piles of food waste are degraded by bacteria, fungi, nematodes, and protozoa at a temperature of about 80 °C. The third stage involves the reduction in microbial activity, decomposition of the food waste, and the formation of the final compost [13].

The composting process yields heat, biodiesel, and bioelectricity. and other clean energy. The leachate generated from the dewatering and composting processes can be treated and used as fertilizer to improve soil fertility. Composting is an easy, ecofriendly, and cheap process. However, the high salinity of the compost products can impact soil environmental quality, increase soil salinity, contaminate soil, and inhibit plant growth [14].

3.3 Incineration

Incineration is the controlled high-temperature burning (rapid oxidation) of a waste. From the crude method of burning, incineration has become a generally embraced modern technique of food waste management. Incineration helps to reduce the quantity of waste disposed into the landfill by between 70 % and 90 % [13]. During the process, the energy in the organic matter of waste food like leftovers, fruits, vegetable peels, eggshells, edible and inedible food from various sources are subjected to high temperature to produce heat, energy, and ash. When 1 g of food waste is incinerated, about 37.7 kJ of heat is generated [13].

For effective processing, food waste should be separated before incineration. The incineration process is a clean, safe, reliable, and stable process that can achieve up to 90 % volume of waste reduction. All the pathogens, pests, and insects are consumed in the incinerator and there is effective control of noise and odour. With the incineration process, small land is required, and there is no need for further decomposition. However, the initial cost of the incinerator is high and the process exacerbates environmental pollution [15].

3.4 Anaerobic Digestion

Anaerobic digestion (AD) is one of the viable and feasible pathways for managing food waste, generating clean fuel, and combating climate change. The four-step process is conducted in a reactor, called a digester, in the absence of oxygen for the conversion of the organic matters in food waste into biogas. The schematic diagram of the anaerobic digestion of food waste to biogas is shown in Figure 4. The overall AD reaction occurs simultaneously in four steps, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis, and is represented in equation 1. Biogas contains approximately 55 % to 75 % CH_4, and 24 % to 45 % CO_2, by volume and trace gases like H_2S, CH_3, N, and moisture [16].

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 \qquad (1)$$

Though AD generates CH_4, H_2S, and other dangerous gases, the remains one of the low-cost and simple technology for converting food waste into renewable fuel. Other advantages of AD include low energy consumption, use of slurry as fertilizer, and serving as an avenue for additional income generation for farmers [17].

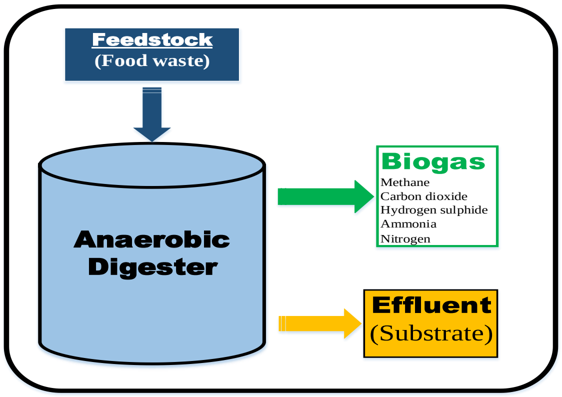

Fig. 4. Schematic representation of anaerobic digestion of *food waste*

3.5 Fermentation

The presence of starch and proteins in food waste makes it an ideal feedstock for fermentation and the production of ethanol, bioethanol, butanol, biopolymer, volatile fatty acids, and other products. Such food wastes are usually subjected to pretreatment to enhance the digestibility of cellulose in the starch and boost the conversion efficiency of the fermentation process. The reaction equation for the fermentation of simple sugar in food waste in the presence of yeast, bacteria, or fungi for the production of ethanol and organic acid is represented in equation 2. Through the same process, the sugars stored in food waste as starch are hydrolyzed to monosaccharides and converted to bioethanol, butanol, hydrogen, and other organic acids such as lactic acid (equation 3), butanol (equation 4) [18].

$$C_6H_{12}O_6 \rightarrow CH_3CHOHCOOH + C_2H_5OH + CO_2 \quad (2)$$
$$C_6H_{12}O_6 \rightarrow CH_3CHOHCOOH + 1.5CH_3COOH \quad (3)$$
$$C_6H_{12}O_6 \rightarrow CH_3CH_2CH_2CH_2OH + H_2O + CO_2 \quad (4)$$

The AD is an easy technique for the conversion of food waste to clean energy and other sought-after products. With AD, the management of food waste is achieved at the lowest cost possible without compromising environmental sustainability. The cost-effective generation of biogas is a major step toward meeting future renewable energy needs. There is, however, a need to appraise the entire process to ensure its overall economic viability.

3.6 Pyrolysis

Pyrolysis is the technology for the thermal degradation of food waste in the absence of oxygen into char, oil, and combustible gases. The process which usually occurs at 300 − 800 ℃ produces biooil, biosyngas (CO + H_2), and biochar. With the systematic variation of the process parameters such as temperature, heating rate, residence time, and feedstock size, the process can also yield acetone, methanol, and acetic acid, particularly during the slow pyrolysis process. Food leftovers, restaurants food waste, and uneaten fruits, and vegetables are pyrolyzed to generate clean fuels and chemicals. Pyrolysis yields up to 75 % biooil at low cost, and short residence time. The raw materials for pyrolysis require minimum pretreatment while biooil, the main product is easy to store and transport. However, the deployment of biooil as compression ignition engine fuels needs further investigations and improvements [16].

3.7 *Gasification*

The gasification technique has been deployed for the conversion of food waste from various sources, fruits, and vegetables into a combustible gas (CO, CH_4, N_2, H_2, CO_2) and some ash, as a byproduct. The process, typically, involves the transformation of carbonaceous constituents into syngas in the presence of air, oxygen, or steam, with temperature ranges of 350-1800 ℃ and 1-30 bar. Thus, the gasification of food waste is an ideal route for the production of biofuel, biomethane, heat, power, and important chemicals [19]. Novel techniques such as plasma gasification and supercritical gasification of food waste ensure a higher yield of syngas at lower temperatures and shorter residence time.

3.8 Hydrothermal Carbonization

One of the advantages of hydrothermal carbonization as food waste conversion technology is its ability to convert food waste with as high as 80-90 % moisture content without first drying the raw materials. With process temperatures as low as 150-350 ℃, food waste of different moisture content simultaneously undergoes hydrolysis, dehydration, decarboxylation, polymerization, and aromatization reactions to produce hydrochar and CO_2-rich gas. Hydrochar is a highly carbonized and energy densified material, similar in composition to lignite coal, with diverse applications such as contaminant adsorbent, raw materials for carbon fuel cells, soil amendment, and renewable solid fuel. However, large volumes of CO_2 are generated and released into the atmosphere during the hydrothermal carbonization process [20].

Table 3. Products, advantages, and disadvantages of some food waste conversion technologies

Food waste	Conversion technologies	Products	Advantage	Disadvantage	Remark
Leftovers, fruits, vegetables, uncooked food	Landfill	CH_4, CO_2, NH_3, manure	• Cheap and economical • Easy and convenient • Requires no technology • Decay food waste serves as manure	• Lack of land • High cost of transportation • Emission of anthropogenic gases • Landfills serve as a breeding ground for insects, pests, and rodents • Generation of offensive odour • Environmental pollution	• Production parameters can be optimized and monitored with technologies • The use of landfill engineered reactors to mitigate the side effects
Fruits, food leftovers, rotten vegetables	Composting	Heat, biodiesel, bioelectricity, fertilizer	• Cheap and economical • Easy and nuisance-free convenient • Ecofriendly and low-cost process • Odour can be successfully controlled • Production of a substitute for organic fertilizer • Production of biofuels, feed additives, and soil conditioners. • Feasible avenue for energy recovery	• Impact on soil environmental quality • High concentration of NH_3 and H_2S • Leads to soil contamination • Increase soil salinity • Retard plant growth • Compost can be used as fertilizers • Improve food production • Unpredictable quality and constituents of compost • Compost may be toxic and contain some contaminants	• Convert biodegradable food waste into usable products • The temperature and other process parameters can be optimized/controlled by the deployment of novel reactors and technologies • The use of a biological deodorization reactor to control the odour
Separated waste food, eggshells, fruit peels, manure	Incineration	Heat, Power, ash	• Reduction in cost of transportation • Smaller land areas required • Heat recovery process • Reduce landfill waste • Pollution reduction • Improved odour and noise control • No generation of methane and other anthropogenic gases • Can achieve more than 90% volume reduction of food waste. • After incineration, no further decomposition is required • The process is reliable, safe, clean, and stable • Easier site selection process • Destruction of pathogens, insects, and pests	• High cost of incinerator installation and operation • Exacerbates environmental pollution • Danger of ash to the environment • Poor fuel quality • Impact public health	There is a need for the competitiveness of food waste incineration for the power generation industry

Leftovers from homes and restaurants, fruits, vegetables	Anaerobic digestion	Biogas, CH_4, fertilizer	• An easy and inexpensive process • Effective odour control • Low cost of bedding materials • Production of manure to grow vegetables • An additional source of income for farmers • Flexible operation • Low energy usage • Contribute to global bioeconomy	• Production of methane and H_2S • Contributes to climate change • High cost of the digester	• Appropriate policy to make food waste a major component of bioenergy and fertilizer production • Promotion of food waste-AD in a Circular Economy framework • Food waste can be pretreated to enhance conversion.
Cafeteria food waste, banana peel, fruit wastes, vegetable waste	Fermentation	Ethanol, butanol, biohydrogen, butyric acid, lactic acid, acetic acid, biopolymers	• Easy and effective process • Contribute to low carbon footprint • Assist in food waste management and environmental sustainability • Does not conflict with the food chain • Low cost and not harmful	• Not economically viable • High cost of storage of raw materials • Contamination and deterioration of raw materials • High reactor cost and operational expenditure	• The fermentation process parameters must be optimized to achieve the utmost benefits from AD. • Further studies are required to reduce the production cost • The deployment of innovative technologies is needed
Restaurant waste, food leftover, uneaten fruits and vegetables	Pyrolysis	Biooil, biosyngas, biochar, methanol, acetone, acetic acid	• Raw materials require minimum pretreatment • Can produce up to 75 % biooil • Generation of clean fuel and chemicals • The process requires a short residence time	• Application of biooil in compression ignition engine is still problematic • Biooil has low volatility, high viscosity, and high corrosive	• Advancements in research and technology are needed to improve the pyrolysis process
Food waste, leftover foods	Gasification	Syngas, biomethane, ash, CO, CH_4, N_2, H_2, CO_2	• Cost-effective • Nonhazardous process • Source of ecofriendly fuels • Contributes to a low carbon footprint	• Emission of NOx • Environmental degradation • High process temperature • Formation of biomass tar	• Plasmas and supercritical water gasification techniques ensure higher yield at lower temperatures and shorter residence time
Food waste, orange waste, peanut shell, leftover foods, sweet potato peel, pomelo peel	Hydrothermal Carbonization	Hydrochar, gas, process water	• Food waste of 80-90 % moisture content can be converted • Low process temperature • Safe and non-hazardous • Dehydration, decarboxylation, polymerization, and aromatization reactions occur simultaneously • Shorter reaction time • Low energy consumption • Ecofriendly • Allows water reuse and heat recovery • Feedstock volume reduction	• Emission of CO_2 • Contribute to carbon footprint	• The process can be catalyzed to improve conversion efficiency • Need for techno-economic analysis for large-scale operation

4. CONCLUSIONS AND RECOMMENDATIONS

Food leftovers, uneaten fruits and vegetables, peels, and other wastes from households, restaurants, supermarkets, and other retail outlets constitute sanitation problems, impact environmental quality, and provide habitat for breeding insects, pests, and rodents. The presence of protein, lipids, carbohydrate, nitrogen, calcium, sodium, and other elements in food waste makes it a feasible feedstock to be converted into biogas, bioethanol, organic acids, biopolymer, volatile fatty acids, and other utilizable products.

The current effort discusses the recent developments in the application of technologies for the conversion of food waste into clean energy, chemicals, and other useful products. Though food waste management techniques such as landfill, composting, and incineration are easy and cheap, they exacerbate environmental pollution, lead to soil contamination, generate offensive odours, impact public health, and produce fuel of poor quality. Pyrolysis, fermentation, AD, gasification, and hydrothermal carbonization are economical, easy to achieve, and contribute to waste-to-energy. Through these conversion technologies, clean and affordable energy, chemicals, and other value-added products are produced for the industrial sector.

More targeted studies are recommended to upgrade these conversion technologies to improve their conversion efficiencies, products quality, and cost of production. There is a need for appropriate policies and programs to encourage the collection and conversion of food waste across various jurisdictions to fully tap the potential of the huge food waste generated globally. More techno-economic analysis and Life cycle assessments are required to ensure safe, nonhazardous, cost-effective, ecofriendly, and sustainable technologies for food waste conversion. There is a compelling need for systematic interdisciplinary and collaborative approaches to utilize the multifaceted benefits obtainable in the conversion of food wastes.

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