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Review

A Review on the Hydrothermal Treatment of Food Waste: Processing and Applications

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Abstract: The amount of food waste is increasing with the development of society and the increase in population; the rough treatment of food waste could result in a serious environmental crisis and waste of resources. Hydrothermal treatment is a promising scheme to achieve the harmless treatment and utilization of food waste. Although there are many studies on the hydrothermal treatment of food waste, there is still a lack of systematic summary and comprehensive analysis of the relevant literature. In this review, we provide an in-depth analysis of the specific impact mechanisms of hydrothermal conditions on the gaseous, solid, and liquid products. Meanwhile, the hydrothermal conversion mechanisms of food waste components are systematically sorted out. The review also discusses the potential application areas for the derived products from the hydrothermal treatment of food waste. Finally, the main challenges and future research directions are proposed to improve the development of the hydrothermal treatment of food waste.

Keywords: food waste; hydrothermal treatment; influence condition; applications

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1. Introduction

With the improvement in the economic level and the improvement of people's living standards, the catering industry has developed extremely rapidly, and the amount of food waste generated shows an increasing trend. Food waste accounts for a large proportion of solid waste, probably ranging from 10% to 33% [1]. According to the food sustainability index 2017 report, the national ranking of food waste production per capita is: Australia (361 kg) > United States (287 kg) > Sweden (200 kg) > Russia (56 kg) > China (44 kg) [2]. Although China's per capita production of food waste is relatively small, the total amount of food waste produced in China is huge due to its large population.

Food waste is the wasted or lost part of the food supply chain [3]. In a broad sense, food waste refers to organic waste generated in the production, sales, processing, and consumption of food, including solid food residues, catering waste water, waste edible oils, etc. [4]. Besides, food waste is mainly composed of starch, dietary fiber, fat, protein, and other organic matter, which has the characteristics of high moisture content and high organic matter [5]. However, food waste can easily induce many serious environmental problems without proper treatment. For example, food waste will produce malodorous gas and sewage in the process of storage and transportation, which will bring great environmental hazards if these pollutants are directly discharged into the surrounding environment.

In the past, nearly 80% of food waste could not be properly treated and recycled, which would cause great damage to the environment and waste resources [6]. Organic carbon and other nutrients in food waste could be converted into energy materials and value-added products through suitable treatment processes [7,8]. At present, food waste treatment technology mainly includes landfill, incineration, anaerobic digestion, composting, and hydrothermal treatment technology. The advantages and disadvantages of different treatment methods are shown in Table 1. The hydrothermal method is particularly suitable for the treatment of wet organic waste [9]. The hydrothermal treatment of food waste is a new resource utilization method with great advantages, which could help reduce the amount of food waste in landfills, protect the environment, and reduce greenhouse gases at the same time [10]. Besides, the economic cost is low, because there is no need for drying [11], and the product has a high utilization value. Therefore, the hydrothermal treatment of food waste is an efficient way of resource utilization, which has great value in reduction, harmlessness, and resource utilization for food waste.

Table 1. Advantages and disadvantages of different food waste treatment methods.

Treatment Process	Advantages	Disadvantages
Landfill	Low cost, simple technology, more used in developing countries	Pollution of groundwater, occupying a large amount of land, and no resource recovery
Incineration	High degree of reduction, suitable for handling hazardous or toxic garbage	High cost, long capital recovery cycle, and low economic efficiency
Anaerobic digestion	High degree of automation, diversified products, high economic value	Need to screen suitable microorganisms, complex technology, discontinuous cycle, and difficult-to-treat biogas residue
Compost	High technology maturity, low cost	Low product value, environmental pollution, long cycle
Hydrothermal treatment	The product has high energy utilization value, simple process, low cost, and short cycle	Hydrothermal treatment products need to be further optimized

From 2010 to 2021 (according to ISI Web of Science™), publications related to the hydrothermal treatment of food waste have been steadily increasing (Figure 1). Research related to the hydrothermal treatment of food waste progressed slowly from 2010 to 2016 and accelerated after 2017. In addition, research on the hydrothermal carbonization of food waste, which was relatively scarce before 2015, became a mainstream research process in recent years, probably because hydrothermal carbonization products had a wide range of applications. For hydrothermal liquefaction as well as hydrothermal gasification, there had been a trend of increasing research year by year, but the growth rate was relatively slow.

Considering that few papers fully describe the relevant information on the hydrothermal treatment of food waste, this review focuses on the processing and the products of the hydrothermal treatment of food waste. All the relevant literature is collected and organized into three categories: hydrothermal carbonization, hydrothermal liquefaction, and hydrothermal gasification for analysis. Firstly, the classification of the hydrothermal process is introduced (Section 2), and then the specific influence mechanisms of hydrothermal parameters on the three-phase products are discussed (Section 3). Afterward, the hydrothermal conversion mechanisms of different biomass components were explored in detail (Section 4). As an important part, the potential applications of the value-added solid, liquid, and gas products derived from hydrothermal treatment of food waste are particularly summarized and discussed (Section 5). Finally, the challenges and development directions are proposed for the industrialization of the hydrothermal treatment of food waste (Section 6). The schematic illustration of this paper was shown in Figure 2.

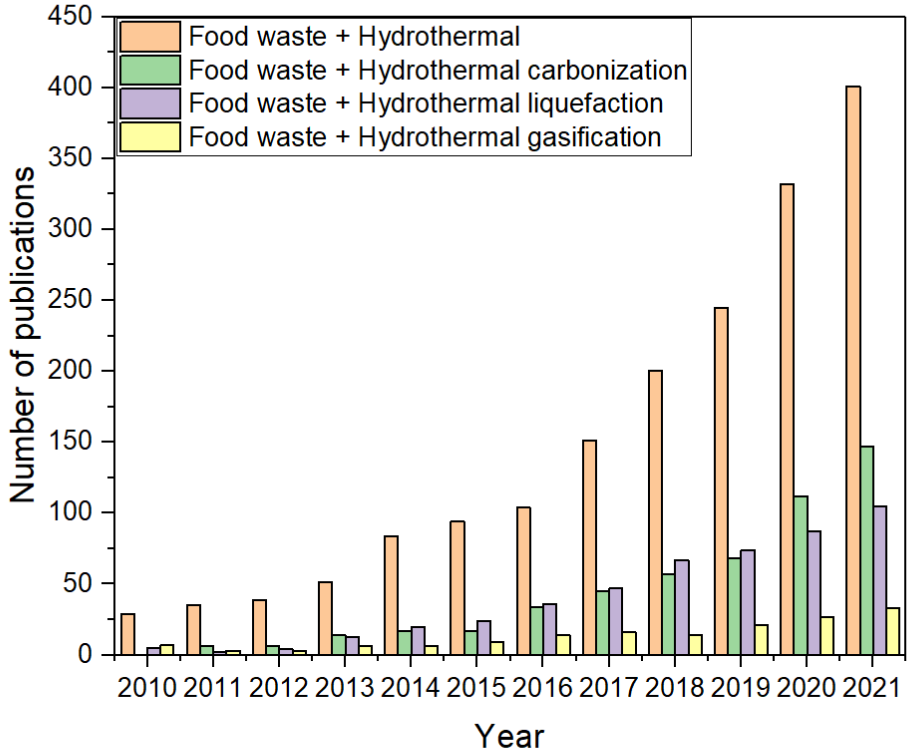

Figure 1. Science Citation Indexed publications on the hydrothermal treatments of food waste in Web of Science.

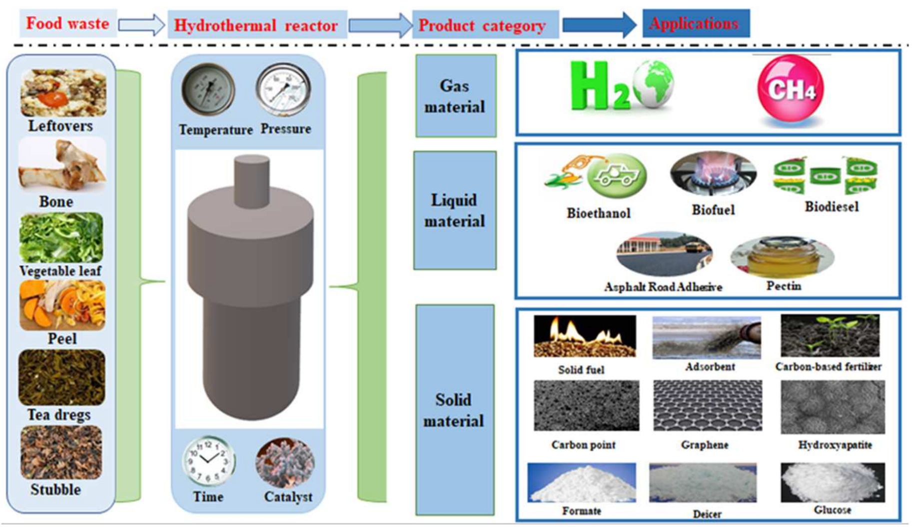

Figure 2. Schematic illustration of this paper.

2. Hydrothermal Process

Hydrothermal treatment of biomass is a very efficient thermochemical conversion process which can transform biomass into valuable biofuels or value-added products [12,13]. According to the pressure and temperature range, the hydrothermal process is divided into hydrothermal carbonization, hydrothermal liquefaction, and hydrothermal gasification.

At present, there are many studies on hydrothermal liquefaction and hydrothermal carbonization and relatively few studies on hydrothermal gasification. Hydrothermal gasification requires higher temperature and pressure, and higher requirements for equipment safety. Table 2 listed the conditions of the three hydrothermal methods.

Hydrothermal carbonization mainly converts biomass into carbon materials (hydrochar) in the temperature range of 180–260 °C under 1–8 MPa [12]. Food residue is hydrothermally carbonized to produce fuel particles, and the prepared solid particles have good combustion properties and can be used as household fuels [14]. Food waste hydrochar is used as other value-added products [15]. For example, food waste could be prepared by hydrothermal carbonization to prepare N-doped carbon dots, which had high selectivity to Fe^{3+} fluorescent probes and could be used as bioimaging materials [16].

Hydrothermal liquefaction occurs generally at 260–374 °C under 10–22.1 MPa [17]. The main product is high-energy bio-oil and other products. Bio-oil is a mixture of substances with different molecular weights such as alcohol, sugar, and furan [9]. The bio-oil produced by the hydrothermal liquefaction of food waste had good quality. The heating value of bio-oil was as high as 34.79 MJ·kg^{-1}, which was expected to become an alternative fuel for petroleum [18]. In addition, food waste is rich in organic matter, which can be hydrothermally liquefied to extract useful products. For example, the extraction rate of pectin was as high as 11.63% by microwave-assisted hydrothermal treatment, and pectin could be used as a thickener and had important commercial value [19].

The temperature range of hydrothermal gasification is above 400 °C, and the energy consumption is very high. The main target product of this stage is synthesis gas, which mainly includes hydrogen and methane. Supercritical water gasification of food residues could produce hydrogen synthesis gas. The supercritical water gasification treatment method is a reliable treatment method for the resource utilization of food waste [20].

Table 2. Classification of different hydrothermal treatment processes for food waste [21].

Hydrothermal Process	Temperature Range (°C)	Pressure Range	Target Product
Hydrothermal carbonization	180–260	1–8 MPa	Hydrochar
Hydrothermal liquefaction	260–374	10–22.1 MPa	Oil
Hydrothermal gasification	>374	>22.1 MPa	Syngas

3. Factors Affecting the Hydrothermal Process of Food Waste

3.1. Temperature

Temperature is the most important influencing factor in the hydrothermal process, and increasing temperature generally contributes to the reduction in food waste. An increase in temperature will lead to a decrease in the production of hydrochar, but it will enhance the combustion performance of hydrochar. Temperature also plays a key role in the production of bio-oil. The elevated temperature will lead to an increase in the production of bio-oil, which has a certain impact on the physical and chemical properties of bio-oil, such as viscosity. In addition, temperature also affects the carbohydrates and other components in the solution. It is necessary to control the appropriate temperature to adjust the content of related components in the oil and liquid phase products. The production of gas in the hydrothermal process is also greatly affected by temperature. Generally, the increase in temperature can promote the production of clean energy gases such as hydrogen and methane.

3.1.1. The Influence of Temperature on Solid Products

Temperature has an important influence on the production of hydrochar. Figure 3 showed the influence of temperature on hydrothermal products. The production of hydrochar decreased from 45% to 35% when the temperature increased from 225 to 250 °C due to the intensification of decarboxylation and dehydration reactions [22,23]. In addition, temperature had an important influence on the physical and chemical properties of hydrochar. The increase in temperature caused the HHV of hydrochar to increase from 15 MJ/kg to 31 MJ/kg. At the same time, high temperature helped to improve the combustion performance and density of hydrochar [24,25]. Conversely, the increase in temperature lead to a decrease in the atomic ratio of O/C and (O&N)/C, indicating that the polarity of hydrochar decreased with increasing temperature [26].

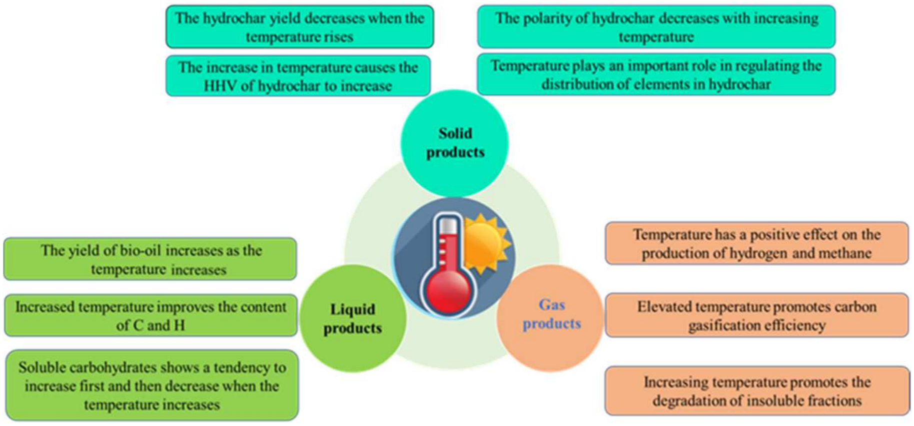

Figure 3. The influence of temperature on hydrothermal products.

Temperature plays an important role in regulating the distribution of elements in hydrochar [27]. The increase in temperature facilitated the removal of ammonia and enriched the nitrogen content of aromatic heterocyclic compounds in the hydrochar [28]. In addition, the increased temperature reduced the production of hydrochar [29], but the content of carbon [16], volatile substances [30], calcium, magnesium and other minerals in the hydrochar elevated [31]. Furthermore, the removal effect of N, S, and Cl was more obvious when the temperature increased from 180 to 260 °C [32]. Especially, with the increase in temperature, the content of pyridine nitrogen and graphitic nitrogen increased, and the use time of carbon dots was shorter, while the content of amino nitrogen and pyrrolic nitrogen decreased [33]. At the same time, temperature was one of the important factors that determined the fate of phosphorus [34].

3.1.2. The Influence of Temperature on Liquid Products

The main components of bio-oil produced by the hydrothermal liquefaction of kitchen waste are C_6–C_{22} compounds [35]. The yield of bio-oil increased significantly as the temperature increased [36–38], but the energy conversion efficiency declined with the increase in temperature [39]. Therefore, it is necessary to determine the appropriate temperature to ensure economic feasibility and energy conversion efficiency [40].

For biofuel preparation, the increased temperature improved the content of C and H and decreased the viscosity. At the same time, the increase in temperature caused the decomposition of organic acids in food waste, leading to an elevated pH of the solution [41]. In addition, the total organic carbon of the liquid also showed a downward trend with the increase in the temperature, indicating that the increase in temperature had a certain promotion effect on the decomposition of water-soluble products [42]. Besides, the soluble carbohydrates showed a tendency to increase first and then decrease when the hydrothermal temperature increased from 100 to 200 °C [43].

3.1.3. The Influence of Temperature on Gas Products

Biogas is generated from food waste through hydrothermal gasification and hydrothermal pretreatment combined with fermentation or other processes. Temperature had a positive effect on the production of hydrogen and methane [5]. What is more, elevated temperature promoted carbon gasification efficiency when studying the kinetics of supercritical water gasification of food waste [4]. The hydrothermal pretreatment temperature of food waste had a certain influence on the production of biogas (hydrogen and methane) produced by fermentation. Increasing temperature promoted the degradation of insoluble fractions, which was conducive to the generation of biogas [44–46].

3.2. Pyrolysis Time

The reaction time is an important factor in the hydrothermal process [47], but the influence degree of the reaction time often needs to be determined in conjunction with other reaction conditions. Generally, under other conditions being fixed, increasing the reaction time helped to increase biogas production, but inhibited the production of hydrochar [48]. The effect of time on hydrothermal products was displayed in Figure 4.

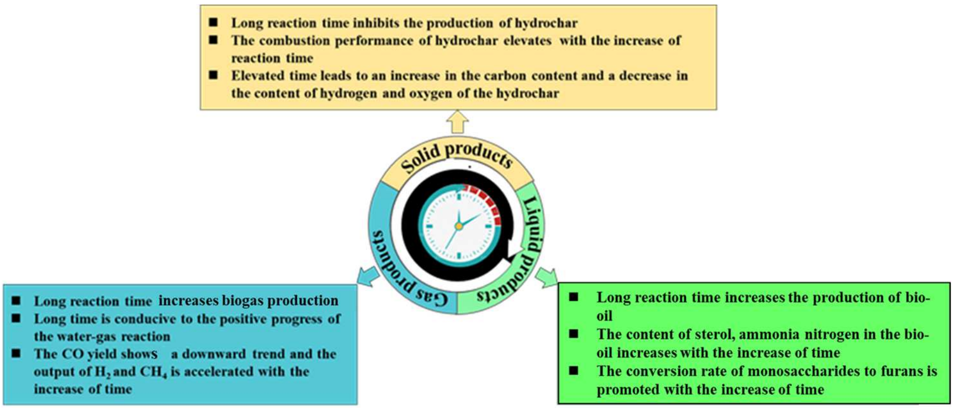

Figure 4. The influence of reaction time on hydrothermal products.

3.2.1. The Effect of Time on Solid Products

The extension of time promoted the condensation reaction of degradation products and increased the conversion rate of hydrochar [49], which reduced the yield of hydrochar [50,51]. In addition, the combustion performance of hydrochar improved and the energy consumption was elevated with the increase in reaction time [52,53]. The elevated time leaded to an increase in the carbon content and a decrease in the content of hydrogen and oxygen in the hydrochar [29]. In addition, the desulfurization of hydrochar was promoted as the prolonged hydrothermal time [53], and the chlorine content in the hydrochar was inversely proportional to the residence time [54]. Besides, residence time had a certain effect on the shape and crystal structure of the hydrochar [55].

3.2.2. The Effect of Time on Liquid Products

Too short a time is not conducive to the hydrothermal reaction of food waste and affects the quality of bio-oil, and excessive reaction time would increase production costs [41]. Under other conditions unchanged, the biotransformation rate and bio-oil output would increase slightly with the time increased [36,38]. However, there was a limit to prolonging the reaction time, increasing the reaction time was not conducive production of bio-oil if the reaction time exceeded the limit [8].

In addition, hydrothermal treatment of olive oil waste was investigated, and the total sterol content in the bio-oil increased significantly when the time increased from 15 to 90 min [56]. As the reaction time was prolonged, the content of ammonia nitrogen in liquid products increased [34], and the conversion rate of monosaccharides to furans was promoted [3].

3.2.3. The Effect of Time on Gas Products

Longer reaction times help to increase the conversion of food waste and increase the gas-phase yield [38]. The prolongation of the reaction time was conducive to the positive progress of the water-gas reaction, resulting in a downward trend in CO yield and an upward trend in hydrogen production [57]. However, the output of CO_2 and CH_4 accelerated with the increase in time due to the hydrolysis, decarboxylation, and dehydration reactions [20,58].

3.3. Catalyst

The catalyst could reduce the activation energy of the hydrothermal reaction, which is an important influencing factor. At present, the relevant catalysts for the hydrothermal process of food waste mainly include the following types: alkaline catalysts, acid catalysts, metal-related catalysts, and biocatalysts. Each type of catalyst has different effects on the hydrothermal process of food waste. The hydrothermal catalysis process requires a lower operating environment, and the energy density and the yield of biofuels increase significantly [59]. Therefore, it is necessary to select a suitable catalyst according to the target product to achieve the purpose of optimal treatment of food waste.

3.3.1. Alkaline Catalysts

Different catalysts are suitable for different feedstocks in the hydrothermal process. Alkaline catalysts have certain requirements on the acidity of lipid feedstocks [60], and the use of basic catalysts in the hydrothermal liquefaction process may increase the hydrolysis of macromolecules, reduce the formation of char, and stabilize the production of bio-oil [61].

Alkaline catalysts such as K_3PO_4, K_2CO_3, Na_3PO_4, and Na_2CO_3 have a good effect on the production of biodiesel and affect the reaction rate in the transesterification reaction. The activity of the catalysts from high to low was $K_2CO_3 > K_3PO_4 > Na_3PO_4 > Na_2CO_3$. The effect of potassium salt was relatively good, but its recovery rate and stability were not good [62].

As the usage of K_2CO_3 increases, the production of hydrochar decreased, and the production of bio-oil and gas increased, indicating that hydrochar could be decomposed to produce tar compounds [42,60]. In addition, the presence of alkaline catalysts promoted the decomposition of short-chain compounds into simple gases. NaOH could inhibit the formation of char and tar, resulting in a higher gas yield. As the concentration of the K_2CO_3 catalyst increased, the yield of H_2 and CH_4 increased, while the yield of CO decreased [20]. Rattana Muangrat explored the influence of alkaline catalysts on the hydrogen produced, the results showed that the H_2 production rate was in the order of NaOH > KOH > $Ca(OH)_2$ > K_2CO_3 > Na_2CO_3 > $NaHCO_3$ [63]. The catalyst could promote the production of H_2 from kitchen waste by regulating the water-gas shift reaction while suppressing the production of bio-oil and water char. In addition, NaOH could absorb part of CO_2 and make the water-gas reaction move positively, thereby increasing the H_2 production rate [63]. Thus, sodium hydroxide is an efficient catalyst for the production of hydrogen by hydrothermal gasification.

3.3.2. Acid Catalysts

The acid-base catalyst is used to convert biomass into bio-oil through a hydrothermal reaction, the quality of biofuel is improved under the action of the acid catalyst [64]. Acid catalysts has the advantages in the conversion of cellulose raw materials for bio-oil production [38]. In addition, acidic conditions might enhance dehydration reactions to produce biocrude with lower H/C ratios [65].

Phosphoric acid contributed to the production of volatile fatty acids during the hydrothermal treatment of food waste [66]. In addition, sulfuric acid concentration had an important effect on the efficiency of food waste conversion to 5-hydroxymethylfurfural. The product yield increased first and then decreased when the catalyst concentration was 0.5 M. However, the product yield increased first and then decreased when the catalyst concentration was 1.0 M [67].

3.3.3. Metal-Related Catalysts

The bio-oil performance improved after catalysis using a ceria catalyst [68]. The homogeneous catalyst Na_2CO_3 or heterogeneous catalyst CeZrOx was used to promote the reaction. The results showed that CeZrOx had a better effect, and the prepared bio-oil had a higher heating value (HHV) and energy recovery [10]. In addition, the concentration of the catalyst has a certain influence on the hydrothermal process of food waste. Sodium methoxide with a concentration of 0.9 wt.% could maximize the yield of methyl esters, and increasing the catalyst concentration would not increase the yield [69]. Furthermore, multicomponent metal oxides had a better catalytic effect than single metal oxides, which might be due to the synergistic effect of acid sites and base sites on the surface of mixed metal catalysts [70]. For example, hydrogen production was the best under the condition of adding two catalysts (Na_2CO_3 and Ni/SiO_2), so there was a synergistic effect between the two catalysts [71].

3.3.4. Biocatalysts

Biocatalysts also have good catalytic performance [72]. Clamshell-derived catalyst is used to catalyze the hydrothermal liquefaction of algae. The bio-oil production could reach 39.6 wt.% when the catalyst loading rate was 0.6 wt.%. In addition, the bio-oil production rate dropped to 37.1 wt.% when the catalyst loading rate increased to 1 wt.% [73]. In addition, fish bone carbon was used to catalyze waste cooking palm oil to produce biodiesel. When the catalyst loading was 2.5 wt.%, the transesterification reaction yield reached up to 98%, because the higher density of alkaline active sites enhanced the catalytic effect [74]. Furthermore, waste coffee grounds were used to prepare nitrogen-doped solid biochar. The biochar was used as a catalyst for the hydrothermal reaction of glucose. The results showed that the nitrogen-rich biochar had an excellent catalytic performance on glucose and helped to quickly convert glucose into fructose, and the reaction activity was equivalent to that of a basic catalyst [75].

3.4. Raw Material

The composition of food waste raw materials is the most fundamental factor affecting the hydrothermal process. The biochemical composition of food waste has a significant effect on both the oil yield and various product compositions and properties [8]. The catalyst, temperature, and time affect the reaction process based on the raw material composition. The influence of the chemical composition of cellulose, hemicellulose, and lignin on the properties of hydrochar was explored, and the lignin hydrochar had a large yield, rough surface, and more benzene rings. In addition, the hydrochar produced by hemicellulose had higher microsphere density and oxygen-containing groups [76]. Furthermore, the effects of carbohydrates, proteins, and lipids on the combustion and pyrolysis characteristics of food waste hydrochar were studied, and carbohydrates helped to enhance the thermal stability of hydrochar. Hydrothermal pretreatment could facilitate the fermentation process and increase the production of volatile fatty acids from vegetable protein products, while there was no significant increase in the production of volatile fatty acids from animal protein products [77]. In addition, the samples with higher starch content produced higher calorific values, and the crude biological product rich in starch had the highest HHV (42 MJ/kg) [78]. However, protein had little effect on hydrochar combustion characteristics [79]. What is more, increased lipid content promoted the combustion reaction and loss of more volatiles, bio-oil yields for meat and cheese were as high as 60% and 75%, respectively [80]. Lipid-based bio-oil had the highest yield and protein-based bio-oil had the lowest yield [81].

Table 3 showed the hydrochar yield of food waste and its calorific value. The yield of hydrochar from food waste ranged from 43% to 66%. Among these, the high content of cellulose and hemicellulose in rabbit food and sweet corn were easily hydrothermally converted under high-temperature conditions, which lead to a lower hydrochar yield. The presence of cellulose and hemicellulose facilitated the dehydration reaction during hydrothermal carbonization [82]. In addition, the higher yield of hydrochar of a mixture of food waste and yard waste was due to the fact that yard waste was rich in lignin, which was more difficult to convert into bio-oil or biogas than cellulose and hemicellulose [83]. The energy content of the hydrochar varied from 10 to 35 MJ/kg depending on the raw material. The high calorific value of hydrochar in restaurant food waste might be attributed to the high content of proteins and lipids [84–87], which could be hydrothermally converted into small molecules with high calorific value. Therefore, the composition of the raw material is crucial to the yield and heating value of the derived hydrochar.

Table 3. Hydrochar yield of food waste and its calorific value.

Feedstock	Temperature (°C)	Hydrochar Yield (%)	Heating Value (MJ/kg)	Reference
Dog food	234–295	55.0	26.0	[88]
Rabbit food	250	43.8	29.1	[89]
Restaurant food waste	225–275	45.0	33.6	[27]
Sweet corn	250	50.0	11.0	[90]
Grape pomace	175–275	46.5	24.3–28.3	[91]
Food waste from a student's hostel mess	200	48.5	30.0	[54]
Food waste and yard waste	220	59.8	27.6	[83]

Moisture content and food waste concentration have important effects on the production of value-added products from hydrothermal treatment. The increase in food concentration was not conducive to the production of hydrogen, the output of CO, CO_2, CH_4, and C_2–C_4 all increased as the food waste concentration increases [57].

Further, the binary mixtures with the synergistic effect of hydrothermal liquefaction on crude bioproduct yield are as follows: protein and cellulose, protein and xylose, cellulose and lignin, and xylose and lignin. On the contrary, soybean oil has an antagonistic effect with lignin [92]. In addition, mixed hydrothermal treatment of food waste with other substances is also an important resource utilization method [93]. Hydrochar prepared by mixed hydrothermal carbonization of kitchen waste and woody biomass had good combustion performance and was suitable for use as solid fuel [94–96]. In addition, the hydrochar prepared by mixing food waste and coal according to the ratio of 1:1 had the best calorific value (31.4 MJ/Kg) [25]. Currently, food waste hydrochar could be used in the related fields of daily life and production in conjunction with other fuels [24]. Furthermore, the mixed hydrothermal carbonization of food waste and packaging materials was investigated, and the concentration of raw materials affected the carbon distribution in the product due to solubilization [27]. Although the existence of plastic was not conducive to the stability of hydrochar, the lower content of plastic promoted the production of gas and improved the reaction efficiency [97].

4. Hydrothermal Reaction Pathways

Food waste is mainly composed of protein, lipids, carbohydrates, cellulose, hemicellulose, and lignin. The hydrothermal conversion mechanism refers to the conversion process of raw materials reacting under hydrothermal conditions to produce the target products. The composition of food waste is complex, and the reaction mechanisms involve a variety of parallel chemical reactions. The specific details of the specific reaction path are unclear and difficult to study. Therefore, the transformation mechanisms of the hydrothermal process of food waste components needs to be explored in detail.

Figure 5 showed a schematic diagram of the hydrothermal process of different biomass components. The conversion process mainly involved five steps: hydrolysis, dehydration, decarboxylation, condensation, polymerization, and aromatization [6]. Lipid, protein, cellulose, hemicellulose, and lignin were hydrolyzed into oligomers or monomers at relatively low temperatures. Dehydration and decarboxylation as well as the polymerization process also occurred during the hydrolysis process [6]. In addition, the increase in temperature caused the decarboxylation reaction and Maillard reaction to proceed, decomposing the monomer material [98]. The hydrolysis of carbohydrates was relatively easy, and the products were simple acids and hydrocarbons with low carbon content. The products of protein hydrothermal reaction were amines, cyclic amides, organic acids, and other substances.

Besides, the hydrothermal process of lipids would undergo the halogenation reaction to produce alkane halides.

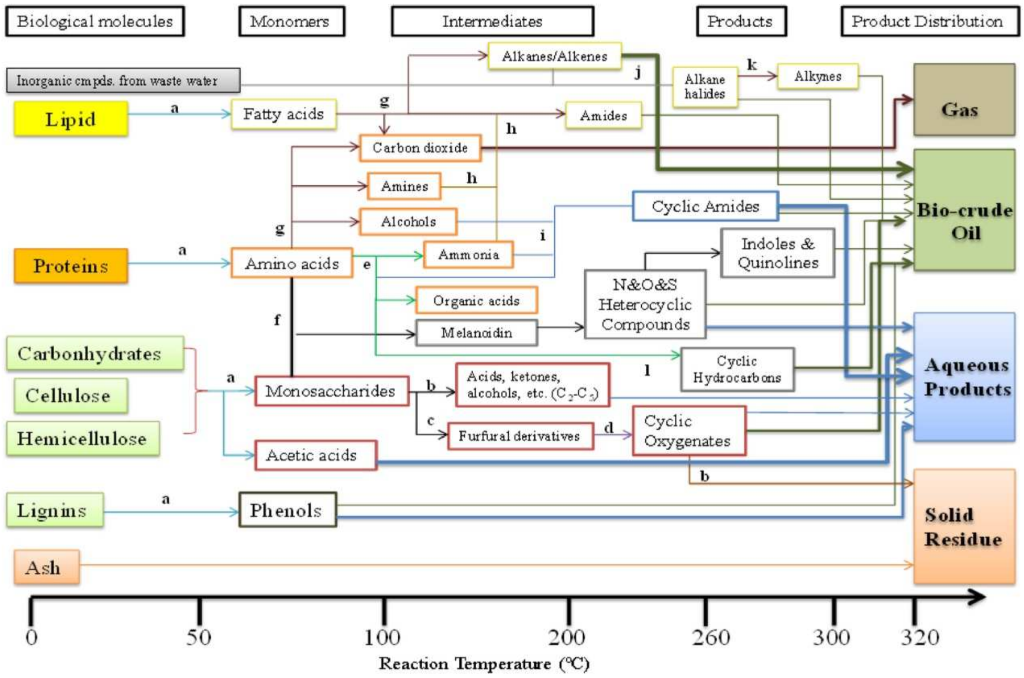

Figure 5. Hydrothermal reaction path of raw material components.: (**a**) hydrolysis; (**b**) decomposition; (**c**) dehydration; (**d**) polymerization; (**e**) deamination; (**f**) Maillard reaction; (**g**) decarboxylation; (**h**) aminolysis; (**i**) cyclization; (**j**) halogenations; (**k**) dehydrohalogenation; (**l**) condensation + pyrolysis. Reprinted from [98] with permission from Elsevier.

5. Applications

In recent years, food waste is an untapped resource with great potential for application. Food waste can produce value-added products through hydrothermal treatment, and hydrochar, gas, and oil products can be widely used in all aspects of society.

5.1. Solid Product

Figure 6 showed the applications of the solid product obtained by hydrothermal treatment of food waste. Firstly, the hydrothermal carbonization of food waste could produce multifunctional application materials and biofuels [99], indicating that hydrothermal carbonization was an effective way of resource utilization of food waste [100]. The generated food waste hydrochar had a higher heating value (higher heating value = ~30 MJ/kg), which was comparable to lignite [54]. The solid fuel produced by hydrothermal carbonization of food waste and other waste could replace traditional fuels [101,102]. In addition, food waste was very abundant and had broad application prospects. The solid fuel prepared by the hydrothermal carbonization of food waste and yard waste could replace up to approximately 11% of global coal consumption [83]. Furthermore, food waste undergoed hydrothermal carbonization to synthesize solid acid and realized the conversion of food waste into biofuel [64].

Carbon dots have good compatibility and fluorescence characteristics, which have important uses in the fields of biomedicine, environmental monitoring, and photocatalysis [103]. Food waste hydrochar could be used to prepare multi-color carbon dots to achieve high-value utilization of food waste [104]. In addition, the nitrogen-doped photoluminescent carbon nanodots generated from fish scales were rich in nitrogen and had rich heteroatom groups, which had good application value [105]. Besides, the carbon dots prepared from pork ribs could be used for rapid detection of dimethoate, and the preparation process had the advantages of low cost and simple operation [103].

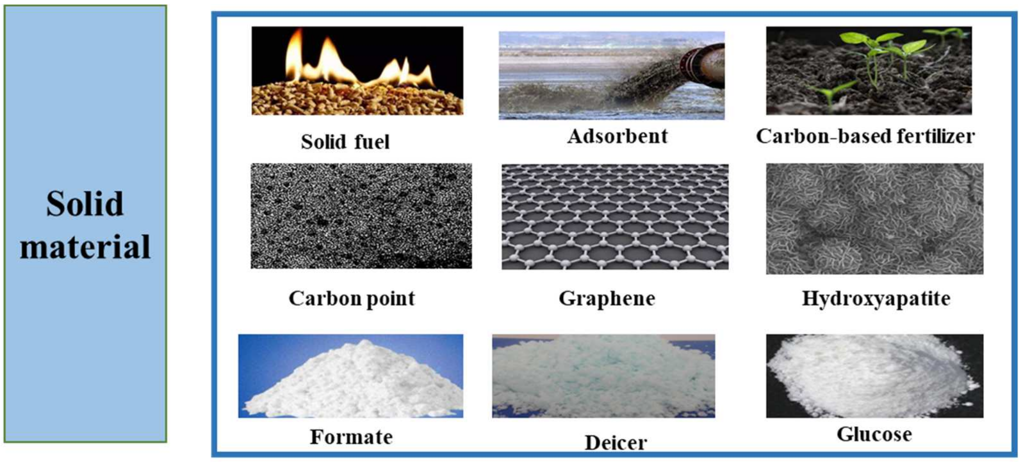

Figure 6. Applications of the solid product obtained by hydrothermal treatment of food waste.

In addition, food waste could be converted into other high-value-added products through hydrothermal carbonization. Formate is a good battery material and hydrogen storage carrier. The food waste was hydrothermally carbonized to prepare formate, and the yield of food residues converted into formate was up to 78% [106]. In addition, eggshells, pomace, and clam shells as a carbon source could be hydrothermally synthesized hydroxyapatite [55,107,108]. The hydroxyapatite extracted from pomelo peel had the best performance, and its shape was similar to the structure of crystalline hydroxyapatite in human bones [55]. Furthermore, bread waste was converted into high-quality graphene flakes by hydrothermal synthesis at a cost of only 3 $\$/m^2$, which was far lower than the current market price (56,000 $\$/m^2$) [109].

At the same time, hydrochar has certain adsorption and catalytic capability [110]. Food waste hydrochar is a potential high-efficiency adsorbent for water pollutants [111], and the specific surface area and pore volume are important factors that affect the adsorption capacity [110]. Food waste hydrochar had a good removal effect on La^{3+}, and the maximum adsorption capacity was up to 108 $mg{\cdot}g^{-1}$ [112]. In addition, hydrothermal carbonization could recover nutrients from food waste. The hydrochar and liquid products produced by food waste could replace about 0.96% and 2.30% of nitrogen and phosphorus-based fertilizers, respectively [34].

Food waste can also be converted into materials for industrial applications through hydrothermal treatment. For example, vegetable waste was converted into acetic acid by hydrothermal method, and then the calcium acetate produced was used as a new green deicing agent [113]. In addition, the carbon-based Fe_3O_4 nanocomposite prepared by the hydrothermal reaction of pomelo peel was a good fruit magnetic solid-phase extraction material [114]. Furthermore, the hydrochar produced from food waste had a similar structure to pure sugars and could be used for application [75,110,115].

5.2. Liquid Product

The applications of liquid material obtained by hydrothermal treatment of food waste were displayed in Figure 7. High-quality bio-oil was produced from food waste through a hydrothermal treatment, which provided an effective way for the resource utilization of food waste [116,117]. The hydrothermal liquefaction of waste edible oil can efficiently produce green biodiesel [72].

In addition, calcined bone could act as a catalyst to promote the transesterification reaction, significantly increasing the yield of biodiesel (up to 98%) [74]. Hydrothermal pretreatment combined with anaerobic fermentation was a high-value utilization method of food waste resources [118]. The chili post-harvest residue was subjected to surfactant hydrothermal pretreatment and fermentation treatment to produce bioethanol, which realized the utilization of waste resources. In addition, hydrothermal pretreatment did not require any additional treatment, and the treatment process was simple.

Figure 7. Applications of liquid material obtained by hydrothermal treatment of food waste.

Food waste (banana peel, watermelon peel, lemon peel, and tomato waste) was hydrothermally liquefied to produce bio-oil. The addition of a catalyst (K_2CO_3) could significantly improve the quality and calorific value of bio-oil [38,40,48]. The heating value of bio-oil was as high as 38.059 kJ/kg [68]. The quality of bio-oil was upgraded to bio-diesel through the distillation and esterification processes, indicating that bio-oil might become a substitute for fossil fuels in the future [119]. Besides, enzyme pretreatment helped with the production of bio-crude oil in the hydrothermal treatment process of food waste [120].

In addition, the hydrothermal treatment of food waste can produce a variety of other high-value-added products. For instance, 1 ton of watermelon rind could produce 1.52 kg of 5-hydroxymethyl furfural through hydrothermal liquefaction, which had certain economic feasibility and market application potential [121]. Besides, the microwave-assisted hydrothermal treatment of mango peel could achieve efficient extraction of pectin, and the extraction rate was as high as 11.63%. In general, pectin could be used as a thickening agent and had important commercial value [19]. Furthermore, the product extracted from food waste through hydrothermal liquefaction could be used as a green binder for asphalt roads, which helped to reduce the use of crude oil [122].

5.3. Gas Product

Food waste can generate natural gas (hydrogen and methane) through hydrothermal treatment. The preparation process is relatively complex and is divided into a single preparation process and a coupled preparation process. The single preparation process includes hydrothermal gasification and supercritical water gasification. The coupling preparation process includes hydrothermal reaction combined with aerobic fermentation, hydrothermal liquefaction anaerobic digestion, hydrothermal pretreatment combined with supercritical hydro thermalization, hydrothermal treatment combined with steam gasification technology, and hydrothermal pretreatment combined with composting. Hydrothermal treatment contributes to the reduction in food waste and the disposal of resources.

The cellulose is hydrothermally gasified, and the selective generation of hydrogen could be achieved at a relatively low hydrothermal temperature [71]. Hydrothermal pretreatment of food waste can break down cellulose into simple substances such as glucose and can increase the ratio of protein to carbohydrate, which is beneficial for subsequent fermentation and other processing [123].

Hydrothermal pretreatment combined with anaerobic fermentation could produce biogas [37,124,125]. The hydrothermal process has a greater destructive effect on food waste and promotes the production of hydrogen [126]. The hydrogen production obtained at 200 °C reached the maximum value of 81.27 mL/gVS [45]. Besides, the methane yield was as high as 511.6 mL/g, and the energy conversion efficiency was as high as 78.6% [43]. Furthermore, hydrothermal pretreatment combined with the aerobic fermentation process could control malodorous gases [127]. For instance, hydrogen production from hydrothermal pretreatment combined with anaerobic fermentation of coffee waste was seven times higher than that by the single fermentation process [128]. Thus, the combined use of hydrothermal pretreatment and anaerobic fermentation has good application prospects.

Hydrothermal pretreatment could reduce energy consumption and reduce costs when food waste undergoes hydrothermal pretreatment combined with supercritical water gasification to produce hydrogen [58]. In addition, hydrochar steam gasification is a potentially efficient process for hydrogen production [42].

6. Challenges and Development Directions of Hydrothermal Treatment of Food Waste

1. Economic analysis of the hydrothermal process of food waste is scarce, so it is necessary to analyze the economic efficiency of hydrothermal treatment to promote industrial applications.
2. At present, the main research is intermittent experimental research, and there is almost no research on continuous hydrothermal treatment of food waste. In addition, there is no relevant continuous hydrothermal equipments on the market, so it is necessary to increase the research and development of relative equipment.
3. The influence of reaction conditions has been discussed a lot regarding temperature and time, but the specific impact mechanisms of the catalyst are unclear. At the same time, there are few studies on influencing factors such as the aqueous phase cycle, pressure, and heating rate. Thus, the detailed study of hydrothermal experimental parameters should be strengthened in the future.
4. In terms of the application of hydrothermal products, there is less research on the utilization of all components of oil, hydrochar and gas products, so it is necessary to strengthen research in this area to improve the high-value utilization of food waste.
5. Most of the current reaction mechanisms are derived from model compounds, which is very different from the actual hydrothermal mechanism of food waste. Therefore, it is necessary to study the reaction mechanism of real food waste and explore the interaction mechanism between different components.

7. Conclusions

Food waste is a potential application resource. However, it is not suitable for incineration or pyrolysis due to the high moisture content of food waste. The hydrothermal process, which does not require the drying of food waste, could be used to prepare value-added products and has attracted widespread attention. The hydrothermal treatment process is mainly divided into three types: hydrothermal carbonization, hydrothermal liquefaction, and hydrothermal gasification. Temperature, time, feedstock composition, and catalysts have important effects on the product. Temperature and catalysts are the main external factors on the yields and properties of hydrothermal products. The interconversion of the solid-liquid-gas products could be achieved by changing the temperature and catalyst, so the suitable hydrothermal processing temperature and catalyst should be selected purposefully according to the target products. In addition, the composition of food waste, an important intrinsic factor in the hydrothermal product, should be concerned first for the generation of target products. The solid, liquid, and gas products derived from the hydrothermal treatment of food waste show good potential in energy production, environmental remediation, and new material preparation, while challenges remain. Hydrochar has good prospects for application in environmental remediation and energy storage, but the high production cost limits its practical application. As for the bio-oil with a certain amount of oxygen, a cost-effective strategy for bio-oil upgradation should be developed. Moreover, considering the complex components of the gas products, the separation and purification of the gases urgently need to be solved. Finally, the exploration of the hydrothermal treatment process and the design of hydrothermal equipments should be strengthened to promote the resource utilization of food waste in the future.

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