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Assessing Energy Potential and Chemical Composition of Food Waste Thermodynamic Conversion Products: A Literature Review

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Abstract: This study examines the considerable volume of food waste generated annually in Slovenia, which amounted to over 143,000 tons in 2020. The analysis shows that 40% of food waste consists of edible parts, highlighting the potential for reduction through increased consumer awareness and attitudes towards food consumption. The study shows that the consumption phase contributes the most to waste food (46%), followed by primary production (25%) and processing/manufacture (24%). The study addresses various thermodynamic processes, in particular, thermal conversion methods, such as torrefaction pyrolysis and hydrothermal carbonization, which optimize energy potential by reducing the atomic ratio (H/C) and (O/C), thereby increasing calorific value and facilitating the production of solid fuels. The main results show the effectiveness of torrefaction, pyrolysis and hydrothermal carbonization (HTC) in increasing the energy potential of food waste.

Keywords: energy; thermodynamic conversions; pyrolysis; torrefaction; hydrothermal carbonization; food waste; energy potential; chemical composition

Citation: Škorjanc, A.; Goričanec, D.; Urbancl, D. Assessing Energy Potential and Chemical Composition of Food Waste Thermodynamic Conversion Products: A Literature Review. *Energies* **2024**, *17*, 1897. https://doi.org/10.3390/en17081897

Academic Editor: Timothy Sibanda

Received: 19 March 2024
Revised: 9 April 2024
Accepted: 12 April 2024
Published: 16 April 2024

1. Introduction

Increasing demand for electricity and limited fossil fuel resources are driving the growing importance of and the search for new, environmentally friendly energy sources [1]. One possible way to obtain such fuel resources is the processing of waste from the agricultural and food industry, which accounts for more than 95% of total waste biomass, which can be utilized in a biogas plant, composting plant, incineration or combustion. However, the main problems with biomass use are its transport and storage, high moisture content, low calorific value, low density and heterogeneous structure. In addition, biomass has hydrophilic properties and is prone to rapid decomposition, creating conditions for the growth and decay of microorganisms. To overcome these properties, fresh biomass (consisting of polymers, carbohydrates, including cellulose and hemicellulose, lignin, lipids, proteins and organic acids) needs to be mechanically, thermally and chemically pretreated [2]. This study is limited to thermomechanical transformations, including pyrolysis, torrefaction, hydrothermal carbonization and gasification.

The focus in many EU and other developed countries is to reduce food waste through effective source separation. Food waste management can be achieved in a variety of ways, including biological technologies and thermochemical processes. Thermochemical conversion is a viable option for the management of MSW in addition to biological processes. Thermochemical processes, such as gasification, incineration, liquefaction, pyrolysis, torrefaction and hydrothermal carbonization (HTC), are likely to be more beneficial for the valorization of FW than anaerobic digestion (AD). However, most of these processes usually require a pre-treatment of the feedstock and a gas cleaning system to avoid emissions such as NOx, SOx, particulate matter and heavy metals. Among these processes, HTC has become a cost-effective method for the thermochemical processing of high moisture biomass, which includes food waste, to produce a product with interesting properties as a biofuel [3].

In recent times, numerous researchers have studied hydrothermal carbonization. For instance, Khoo et al. [4] investigated the effects of temperature and residence time on the physical and chemical properties of the resulting products. From the research, it was found that the carbon yield significantly decreased with increasing temperature. However, this method increased the heating value compared to raw biomass [4].

Food waste, according to this definition, includes edible and inedible parts. The inedible part of food is the part of the food that was never intended for human consumption and is more difficult to avoid, e.g., peels, skins, bones, seeds and shells. The current definition of food waste does not include food waste destined for processing into animal feed, food for charitable purposes, paper tissues collected as bio-waste and packaging that is thrown away with the food waste. In the analysis itself, the authors use different measurement methods, which makes it even more difficult to compare the results, as the studies are very limited [5]. Another definition of FW is defined as food and inedible parts of food returned from the food supply chain that require recovery or disposal [6].

In addition, the fluctuation range of harvests must be considered, so the data must be measured over several consecutive years. Direct measurement of food waste by researchers who are experts in this field is cited in the literature as a sufficiently reliable method [7]. There are studies in the literature that, based on various sources, provide estimates of the amount of food wasted at the EU level. After reviewing the studies at the EU and global level, the results for the EU range between 158 and 298 kg/year/capita. These estimates are due to differences in the different studies, system limitations, objectives and methods [8].

The proximate and ultimate analyses of torrefied biomass are optimized during the torrefaction process to enable the production of powdered biochar with high calorific value and low moisture content [9]. Lu et al. investigated that it is possible to obtain more energy from carbonaceous char as solid fuel than from the gases produced during anaerobic digestion [10].

HTC has great potential for the future conversion of food waste, transforming it from a lengthy process into a simple and rapid one. In a short time, it converts heterogeneous and wet biomass (with water content ranging approximately between 50% and 95%) into sterile and storable char [11].

The chemical and physical composition varies depending on the type of food waste. These differences pose a major challenge to the adoption of existing international standards for the disposal, recycling and assessment of food waste. There is also a general consensus in the literature that current technologies for food waste recycling need to be further improved to be economically viable. Various studies have highlighted the importance of improving downstream bioprocesses, leading to the creation of an integrated biogas plant for the treatment of food waste. The study highlighted the benefits of converting food waste into energy [12].

The objective of this paper is to address the composition of food waste and to study its role in biorefineries to identify nutrient synergies and their use in thermal conversion processes. The novelty of this study represents the fact that there is no research on different types of waste food for the presented thermochemical process future work.

2. Sources and Types of Food Waste

According to EU data, the total amount of food thrown away in 2021 was more than 58 million tons. Household food waste accounted for around 31 million tons of fresh weight or 54% of the total. Figures for Europe show that over 88 million tons of food is wasted each year from primary production to consumption, at a very high cost of an estimated €143 billion. In addition, 72% of food waste is generated by households and 17 million tons by the processing sector. In terms of food groups, the highest percentage of loss is in roots, tubers and oilseeds (25%), with fruit and vegetables accounting for around 22%, meat and livestock products accounting for 12%, and cereals and pulses at 9%. Recent studies have shown that fruit and vegetables are the two food groups that generate the most waste in Europe. In line with these recommendations, food waste from different sectors of the agri-food industry (vegetables, fruit, beverages, meat and seafood products, etc.) is a promising and cost-effective source of functional or bioactive compounds. Excess food products are also used in nutraceuticals and pharmaceuticals or converted into animal feed products [13].

In some studies, apple pomace has been selected as the primary food by-product. As a major waste product of the apple processing industry, they have great potential for use in the biotechnology industry and also due to their large volume. A total of 0.7 million tons of apple pomace is produced annually in the EU. Another area is the growing consumption of meat, which is increasing, while the demand for lower quality products such as blood, offal or certain muscles is decreasing. According to EU figures, 2 million tons of animal blood are produced in the EU every year. Brewing industry residues are also an important source of waste in the EU, with European breweries producing around 4 million tons of waste brewing grains per year [14].

Food and kitchen waste are available all over the world. The individual process valorization of these foodstuffs requires the proper identification and classification of residues and raw materials. A qualitative and characteristic classification of foodstuffs can be useful, i.e., by group of individual foodstuffs; these are fruit and vegetables, starchy foods, meat, fish and other foodstuffs, such as raw and cooked food, salads, bread and also desserts [15].

Food waste can originate from plants or animals and is generated by different parts of the food supply chain (Table 1) [16].

Different categories have been proposed depending on the causes of waste: old and unprocessed food due to poor logistics, over-processed food due to poor evaluation, and inadequate food handling and waste due to oversized portions. Studies look at the average composition of household, institutional and catering waste and show that these residues have a pH ranging from 4.2 to 6.7 and 52–88% water. In particular, the high water content can lead to nutrient loss during dehydration and can lead to a reduction in calorific value. Fractions rich in polysaccharides are thus a good source of carbon for bioconversion processes [15].

A shared waste collection facility was likely to be the most cost-effective. It would be designed to process different waste streams from the food industry, households and other different sectors [17].

On the other hand, food waste is a sustainable source of energy despite disposal problems and environmental impacts. Food waste from markets has attracted a lot of attention because of its rich organic composition. It has an energy value that can be converted into value-added products, such as materials, biochemicals, enzymes and biofuels. Biofuel production by various methods such as intermediate pyrolysis, fast pyrolysis, hydrothermal liquefaction or gasification and subsequent Fischer–Tropsch synthesis are the main thermochemical methods for the conversion of biomass into liquid hydrocarbons. Thermocatalytic reforming (TCR) is the next new technology, which is a combination of intermediate pyrolysis and post-catalytic reforming. This process involves intermediate pyrolysis in which thermal heating and decomposition of the biomass takes place in the complete absence of oxygen with intermediate heating rates and solid retention times (in minutes). The next step is reforming, which takes place at elevated temperatures in the absence of oxygen, with appropriate physical and chemical properties. The recovery of this type of waste thus depends on the type of pre-treatment and the extent of recycling [18].

Table 1. The types and sources of individual food wastes generated in different parts of the food supply chain.

Source	Plant Sources	Animal Resources
Primary production	- Unharvested crops. - Crops left in the field after harvest. - Harvested unsold crops. - Fruit and vegetables in the process of decomposition. - Crops damaged by machinery or other improper handling. - Loss of food due to improper storage. - Worse crop quality (weather conditions, cultivation method)	- Discarded fish. - Loss of food due to inadequate storage. - Dead animals during breeding. - Loss of milk due to animal disease.
Processing and manufacturing	- Causes in the processing (inefficiency, pollution, etc.). - Inedible part of food (wrappers, seeds, bones, fruit peelings, etc.). - Low utilization of by-products. - Few manufacturing defects (food recalls) - Inedible parts of food (created when separating the edible part of food during processing). - Food damaged due to inadequate packaging.	
Retail and marketing	- Food spoiled due to inadequate refrigeration/storage equipment. - Food with an expired shelf life. - Unsold food. - Damaged packaging. - Food withdrawn and recalled due to health risk, inadequate quality or inadequate labelling.	
Final preparation and consumption	- Improper food storage. - Too large portions or purchased quantities. - Expiration dates of edible food. - Not enough meal preparation planning. - Unattractive to consumers. - Inedible part of food (bones, fruit pits and peels, etc.).	

Food waste consists of lipids, hemicellulose, cellulose, starch, lignin and protein, which make up 82–96% of the total volatile compounds. They are similar to other carbonaceous solid wastes used in bioenergy production (in woody biomass and agricultural and general municipal solid wastes). They are relatively much richer in lipids (saturated fats) and proteins. This makes them particularly attractive for processing into biofuels and chemicals. On the other hand, lipids can be inhibitory during methane (CH4)-producing processes (e.g., anaerobic digestion) as they increase the methanation time. Protein is also a large proportion of food waste and is associated with a proportion of meat and dairy products together with lipids. Most food waste contains a high water content (on average 80 % by weight). The high water content makes food waste susceptible to biodegradation and poses a major problem for long-term storage. For this reason, reducing the water content, which should normally be below 10%, is an essential pre-treatment step. Pyrolysis and gasification reduce the energy input during treatment and thus avoid negative impacts. The value of the O/C ratio indicates the degree of polarity, and the H/C atomic ratio indicates the degree of aromaticity and stability of the samples. Summarizing the results from different studies, it could be concluded that the carbon content of food waste ranges from 40.0 to 60.0%, hydrogen from 5.0 to 13.0%, nitrogen from 1.5 to 6.0% and oxygen content is defined in a wider range from 17.0 to 41.0%. According to some reports, high oxygen content in individual food samples may result in a high proportion of liquid in pyrolysis, while on the other hand, low oxygen content is desirable as the reduction of oxygen compounds improves the stability of the bio-oil [12].

Evidence from various studies suggests that elevated HHV in food waste is usually characterized by a high proportion of meat and dairy products in a given sample (HHV of meat > 25.2 MJ/kg) [19].

As mentioned earlier, animal products are rich in protein and fat, while fruit, vegetables and cereals are higher in carbohydrates. Given the elemental composition of proteins, fats and carbohydrates, there is a large amount of carbon present, which makes discarded food easily biodegradable [20].

3. Materials and Methods

Pyrolysis, gasification, liquefaction, carbonization and torrefaction are common thermochemical processes for converting biomass from food waste to produce liquid, solid and gaseous products. The effect of these processes depends on the oxygen supply and the reaction temperature. Almost all biomasses can be burned if their calorific value is high enough, which can reduce the consumption of fossil fuels [21].

A number of countries have targeted legislation and regulations for solid waste management, but implementation varies widely. The most common food waste treatment methods in use today are anaerobic digestion, composting, incineration, fast pyrolysis, gasification, hydrothermal carbonization and hydrothermal liquefaction (Figure 1) [22].

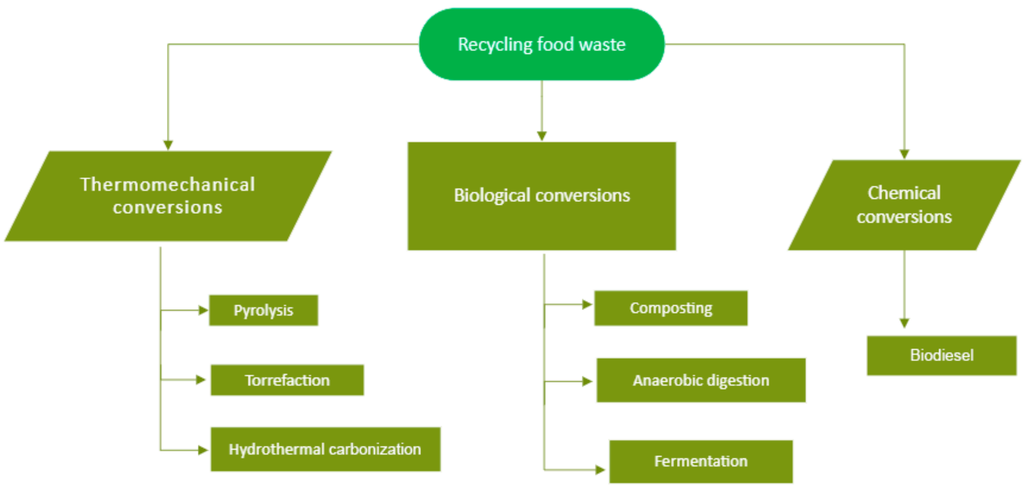

Figure 1. Typical food waste recovery technologies.

3.1. The Methods for Thermochemical Conversion

3.1.1. Torrefaction

Torrefaction (also known as low-temperature pyrolysis) is one of the most efficient processes for treating biomass. The process is carried out between 200 °C and 300 °C in a neutral atmosphere, at atmospheric pressure and with a residence time of up to 90 min. The absence of oxygen inhibits the combustion process and accelerates the thermal decomposition of the torrefied biomass [2].

The final result of the torrefied biomass is influenced by the temperature, duration and flow rate of the carrier gas, particle size, composition and presence of catalyst, etc. [21].

The resulting biochar typically has much better physical and chemical properties than raw biomass; it has a higher calorific value, higher energy and mass density, improved hydrophobicity and better friability, giving it similar properties to coal [23].

Torrefaction causes the breakdown of hemicellulose and the dehydration of cellulose and lignin [24]. Studies have shown that the oxygen–carbon ratio is reduced, and the energy value is increased [2].

The process is particularly suitable for treating food waste with high moisture content and subject to biodegradation. One of the disadvantages of torrefaction is the presence of dioxins (by-products of incineration in various industrial processes) and dioxin-like contaminants in the charred end product [25].

As the moisture content of the biomass is significantly reduced during the torrefaction process, the moisture content of the final product is about 1 to 3% [2].

Hydrogen is also an important energy source in biomass combustion, but it is usually present in biomass in the form of CH or OH bonds. The oxygen contained in biomass is useful in combustion, but a higher oxygen content reduces the calorific value of the biomass. It is important that the torrefaction process achieves a calorific value close to that of coal (25–35 MJ kg^{-1}). Recently, torrefaction has been used as an efficient method of biomass pre-treatment for the production of bio-oil from pyrolysis [21].

3.1.2. Pyrolysis

Pyrolysis produces energy from waste biomass in the form of solid and liquid biochar and synthetic gas [26]. This thermal decomposition process takes place in the absence of oxygen. The chemical reactions are complex and consist of several steps. The process takes place in a pyrolysis reactor in two stages. The first stage produces a liquid, solid char and gas, and the second stage produces a liquid bio-oil. In the absence of a condenser, all the feedstock is thermally decomposed into gases, which are then used in the combustion chamber to provide heat [27].

The pyrolysis process is carried out at high temperatures, ranging from 300 to 1000 °C. The operating conditions have a strong influence on the resulting products, as fast pyrolysis uses finely ground feedstock, which gives high bio-oil yields. In slow pyrolysis, however, the bio-oil content is much lower. The operating parameters can be varied to obtain the desired range of products, which depends on the feedstock selected [26].

3.1.3. Gasification

The gasification process usually takes place in a temperature range between 600 °C and 1200 °C. Gasification is usually divided into gasification, steam gasification and supercritical water gasification, depending on the reaction environment. Gasification of biomass is an oxygen-deficient thermal process in which the feedstock is converted into a gaseous product, where the main products are H2 and CO. The improved properties of biomass are higher calorific value and lower volatile content [21].

Gasification is a thermochemical partial oxidation process that takes place at high temperatures. During the gasification process, the solid feedstock is transformed into a gaseous fuel. The composition of the resulting gases depends strongly on the type of feedstock, but the product produced is mainly composed of methane, carbon monoxide and hydrogen [28].

3.1.4. Hydrothermal Carbonization

Hydrothermal carbonization is the process of converting selected biomass into energy- and carbon-rich charcoal. It involves hydrolysis, polymerization, dehydration and carbonization processes taking place at moderate temperatures between 180 and 260 °C and pressures between 35 and 55 bar. As food waste contains moisture, it is used as an organic solvent at higher temperatures and pressures when exposed to HTC due to its reduced dielectric constant. Such exposure of food waste is not economically feasible in the above processes due to the intense evaporation of the moisture present [29].

The hydrothermally produced solid product can be used as a fuel, adsorbent or catalyst, while the use of the liquid product is limited. The main constituents of the hydrothermally produced gaseous product are carbon dioxide and trace hydrocarbons [30].

The HTC process reduces the ratio of hydrophilic to hydrophobic substances, converting organic feedstocks into hydrocarbon-rich solids. Studies have confirmed that the use of HTC in conjunction with a mechanical water removal process is more energy efficient than using a conventional thermal drying process to control water content. The use of a combination of HTC and pyrolysis is a promising method to reduce the high energy efficiencies associated with water evaporation [31].

3.2. Technologies Depending on FW Type

In Table 2, several technological options for processing food waste are listed. The selected technology should be simple and capable of handling the heterogeneous nature and moisture content of food waste. It must allow for relatively short treatment times, on-site separation and separation at transfer stations to continuously reduce the volume of waste and thus the need to transport it to landfill [22].

Table 2. Characteristics of technological processes for treating food waste from a technical and economic perspective [22].

Technology	Characteristic	Processing Cycle	The Results
Incineration	- Large quantities required. - Necessary mixing for uniform quality.	- Large amounts of different heterogeneous biomasses, including food waste.	- Heat for steam production and heating. - Ash. - Heavy metals.
Fast pyrolysis	- Fast processing. - Pre-treatment of drying the raw material to a moisture content of 10–15% is required.	- Some food waste is unsuitable because it contains moisture.	- 60–75% of liquid product. - 15–20% biochar. - 10–20% non-condensable gases.
Gasification	- Pre-treatment of drying the raw material to a moisture content of 10 to 20% is required. - Waste must be carbonized. - Part of the waste is not suitable for gasification.	- Pre-drying process is required.	- Synthetic gas.
Hydrothermal Carbonization (HTC)	- Waste can be wet. - Acetone is required for extraction. - Crushing into a mixture.	- Short processing cycles.	- 49–75% of the carbon present is retained in the charcoal. - 20–37% in the liquid phase. - 2–11% in the gaseous phase.
Hydrothermal liquefaction (HTL) Torrefaction	- Water and inexpensive catalyst are required. - There is no sensitivity to wet waste. - A portion of food waste in municipal waste, due to its high moisture content, is not suitable for torrefaction	- It processes heterogeneous wet waste. - Needs to be crushed into a relatively homogeneous mixture. - Very rapid processing cycles.	- By-products include the liquid phase (approximately 85% of the hydrolysate)—mixed solid phases (approximately 15% as dry weight). - Produces solid fuels with high energy content and improved combustion properties.

4. Results and Discussion

To summarize the data from the Statistical Office of the Republic of Slovenia (SURS), over 143,000 tons of food waste was generated in Slovenia in 2020. The amount of food waste is increasing annually and has increased by an average of 3% per year in the period from 2013 to 2021. According to SURS estimates, 40% of food waste consists of edible parts, which could be significantly reduced with appropriate consumer awareness and the right attitude towards food. The remaining part consisted of peels, skins, seeds, etc., which are considered inedible parts of food waste. Although the average annual amount of food wasted by Slovenians is lower than the European average, a comparison between 2017 and 2020 shows an increase in the amount of food wasted and thrown away per capita, from 64 kg to 68 kg [16].

The amount of food waste produced at different stages of the food supply chain is shown in Figure 2 [32].

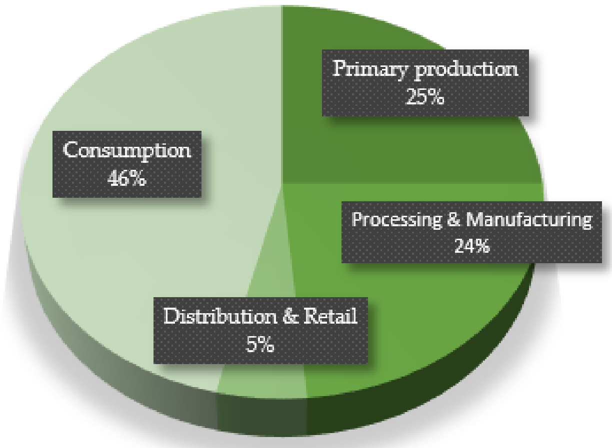

Figure 2. The amount of food waste produced at different stages of the food supply chain.

Unlike biochemical conversion, in which the substrates are slowly broken down during anaerobic metabolism, thermal conversion is an energy-intensive way of obtaining energy from biomass. During thermal conversion, the high heating values of the biomass and processes such as dehydration, deoxygenation and dihydroxylation are determined. The calorific values of biomass are crucial for the selection of biomass for energy production and the assessment of its potential for economic feasibility. The thermal values of biomass samples can be determined by computational models or direct measurements [33].

Table 3 shows the approximate and final values of selected biomass produced from different types of food waste, both dry and ash-free values, and a summary of the calorific contents for each biomass.

High-moisture food waste has a low calorific value. The low calorific value is also due to the high elemental oxygen-to-carbon (O/C) ratio. The high HHV of animal-based food waste is probably due to the higher hydrogen-to-carbon (H/C) ratio. During combustion itself, combustible gases are released, which are associated with a large amount of energy. A number of studies have reported that most of the calorific values of food waste were not only below a combustible index of 23 MJ/kg but also higher than a combustible index of 14.5 MJ/kg. This points to the fact that most types of food waste cannot be considered as alternative renewable fuels without pre-treatment. These chemical components are present in hydrolyzed form in liquid food waste. The chemical and elemental composition (carbon-C, hydrogen-H, oxygen-O, sulphur-S, nitrogen-N, etc.) of food waste and charcoal makes it possible to determine the quality of the fuel or charcoal produced from food waste. Lignin-rich food waste is desirable for the production of highly efficient solid fuels because of its high thermal stability in comparison with cellulose and hemicellulose. The lower the atomic O/C ratio, the higher the calorific value of the solid fuel produced. All food wastes with a low fuel ratio are less reactive unless pre-treatment is carried out [29].

Table 4 shows the values of elemental composition in biochar obtained from different biomass sources through the processes of torrefaction and hydrothermal carbonization, and it emphasizes the lack of research in the field of torrefaction.

Table 3. Approximate and final values of selected biomass derived from different types of food waste, dry and ash-free, and a summary of the calorific values for each biomass.

Biomass	C	N	O	H	S	Ash Content	VM %	FC %	HHV (MJ/kg)	O/C	H/C
Animal-based [33]	[30]										
Egg	23.49	3.03	7.65	23.11	1.02	62.50	18.90	18.60	10.09	1.24	1.17
Fish	44.42	7.41	28.67	7.90	1.25	10.35	75.56	14.09	15.20	0.49	2.12
Meat (Beef fat—processing)	70.95	0.70	16.90	11.01	-	0.44	99.50	0.06	36.64	0.11	1.16
Manure and whey	28.2	1.7	20.3	3.6	0.5	45.7	-	-	15.9	0.54	1.53
Plant-based [33]	[30,34]										
Pumpkin	48.85	3.50	39.33	6.67	-	1.65	92.32	6.03	19.12	0.60	1.63
Potatoes	42.20	2.15	48.05	5.84	-	1.76	93.39	4.85	14.12	0.86	1.65
Carrot	42.45	2.17	47.63	5.55	-	2.19	81.86	15.95	13.88	0.84	1.56
Grape pomace (GP)	44.14	1.27	41.91	6.18	-	6.50	76.22	17.28	-	0.79	1.68
Garlic	42.96	1.08	37.40	5.49	0.88	12.20	67.64	20.17	15.83	0.65	1.52
Peanut	59.27	3.30	22.39	8.18	-	6.86	93.95	0.81	27.77	0.29	1.64
Apple chip pomace (ACP)	47.94	1.96	40.90	6.66	0.07	2.47	81.65	15.88	-	0.64	1.66
Rice husk	46.26	1.36	45.92	6.46	-	11.80	73.50	14.70	16.20	0.74	1.67
Corn stalk	45.67	0.31	47.60	6.42	-	2.59	87.19	2.59	17.65	0.78	1.68
Wheat straw	51.25	0.63	42.81	5.18	0.13	3.70	80.00	7.80	17.10	0.63	1.21
Empty fruit bunces	48.30 45.53	1.00	43.70	6.66	0.34	3.00	82.21	10.41	19.45	0.68	1.65
Olive pulp-including kernels	51.91	1.65	40.45	5.99	-	3.10	75.20	21.80	21.70	0.58	1.38
Coconut husk	50.05	0.41	43.63	5.80	0.10	3.40	61.80	34.80	19.10	0.66	1.39
Banana peel	47.50	1.00	45.50	7.03	-	8.30	-	-	9.19	0.71	1.77
Energy crops	40.30	2.1	24.0	4.6	0.3	28.7	-	-	16.4	0.44	1.37
Vegetable, garden and fruit waste	29.50	2.0	21.4	3.0	0.3	43.8	-	-	14.9	0.54	1.22

Table 4. A comparison between torrefaction and hydrothermal carbonization of certain food waste, including their chemical composition and energy value.

	Torrefaction [24,34]									Hydrothermal Carbonization [12,33–35]								
Biomass (Animal- and Plant-Based)	**C**	**N**	**O**	**H**	**S**	**Ash**	**HHV (MJ/kg)**	**O/C**	**H/C**	**C**	**N**	**O**	**H**	**S**	**Ash**	**HHV (MJ/kg)**	**O/C**	**H/C**
Manure and whey	-	-	-	-	-	-	-	-	-	35.5	-	13.6	3.8	-	-	14.5	0.28	1.28
Chicken	-	-	-	-	-	-	-	-	-	66.1	6.46	16.22	9.9	0.3	1.02	32.97	0.18	1.8
Grape pomace [35]	-	-	-	-	-	-	-	-	-	61.46	1.72	29.97	5.16	-	1.69	-	0.36	1.01
Apple chip pomace	-	-	-	-	-	-	-	-	-	62.10	2.26	27.86	6.94	0.07	0.77	-	0.34	1.34
Rice husk	55.82	0.91	-	-	0.02	21.24	-	-	-	49.26	0.68	43.57	6.48	-	12.10	16.50	0.66	1.57
Corn fiber	-	-	-	-	-	-	-	-	-	49.25	0.25	44.28	6.21	-	0.53	19.47	0.67	1.15
Wheat straw	-	-	-	-	-	-	-	-	-	53.02	0.63	40.88	5.36	0.11	1.30	19.30	0.57	1.21
Empty fruit bunces	47.07	1.35	42.24	4.95	0.11	-	-	0.67	1.26	54.30	1.02	38.29	4.14	0.24	4.16	22.07	0.53	0.91
Olive pulp-including kernels	51.8	0.1	41.5	6.1	0.02	0.5	19.6	0.60	1.41	61.16	1.68	30.63	6.53	-	4.80	24.30	0.37	1.28
Coconut husk	-	-	-	-	-	-	-	-	-	59.52	0.50	34.17	5.71	0.10	0.30	23.90	0.43	1.15
Energy crops	-	-	-	-	-	-	-	-	-	41.2	-	21.9	3.9	-	-	23.1		
Raw vegetables, fruits and peels [12]	55.86	3.15	10.93	5.15	-	24.91	23.83	0.15	1.10	-	-	-	-	-	-	-	0.52	1.41

Elemental composition analysis, which includes hydrogen (H), carbon (C), nitrogen (N), sulphur (S) and oxygen (O), has a central role to play in assessing the properties of biomass and coal and allows for an accurate material balance and determination of calorific value. This analysis can be performed individually or in combination to obtain comprehensive results, with C, H, N and S expressed on a dry basis. In particular, the hydrogen content affects the amount of heat of combustion and, conversely, the C content. Although oxygen promotes combustion, it reduces the calorific value due to its diluting effect on carbon. Elemental analyses of biomass generally show a higher proportion of O and C, followed by H, N and S, although the proportions vary depending on the type of biomass [33].

In the process of torrefaction of biomass, the decrease in the O/C ratio is due to the increased lignin content, which has a lower O/C ratio than cellulose and hemicellulose. This shift reduces the oxygen content, enriches elemental carbon and consequently increases the calorific value. In addition, the H/C ratio decreases due to the release of volatile compounds, but this is attenuated by the increasing lignin content at higher torrefaction temperatures, which affects the balance between hydrogen and carbon. Although torrefaction increases calorific value due to the lower O/C and H/C ratios, it also results in weight loss, which offsets some of the calorific benefits gained, especially at higher temperatures. Therefore, torrefied biomass has a higher carbon content and lower oxygen content compared to raw biomass, which has a positive effect on the O/C ratio and calorific value (Table 4).

Based on the measured values of biomass products, it is evident that food waste with high moisture content and high O/C ratio has a low heating value (HHV). The understanding of the HHV of fuels and substrates is determined on the basis of the atomic ratios of O/C and H/C. The high heating value of animal waste biomass is most likely due to the higher H/C ratio, as combustion releases a large amount of gases [33]. Food waste with a low fuel ratio is less reactive unless preprocessing is used.

Waste containing meat with a higher carbon content (70.95%) had a higher calorific value (36.46%), which is in line with the claim that high-carbon biomass has a high calorific value. The predominantly low HHV values of the different biomass food wastes are consequently attributed to the high oxygen levels, which do not promote combustion but have a negative effect on the conversion of biomass to liquid fuel. Pyrolysis as a biomass conversion process lowers the atomic H/C and O/C ratios, increases the heating value and thus achieves better solid fuel production [36].

As shown in Table 2, several technological options are available for the treatment of food waste. When selecting a technology for the treatment of food waste, a number of aspects need to be carefully considered. The technology selected must be simple and able to cope with the heterogeneity of food waste and its moisture content. It must generate materials or products with energy value that can be used for further applications. In addition, it must allow relatively short recovery cycles [22].

Compared to other municipal waste fractions, food waste is characterized by its high moisture content and poses a challenge for efficient incineration or conversion processes. A high moisture content, especially in fruit and vegetables, can lead to the release of dioxins when incinerated together with organic substances. This moisture content significantly lowers the heating value of food waste and thus reduces its energy quality. The varying characteristics of different food waste sources, compounded by limitations such as small sample sizes and inconsistent categorization, underscore the need for comprehensive analysis to refine energy models. The moisture content of food waste ranges from 1.59% to 74%, exceeding the variability of coal. The complex chemical composition of food waste, including lignin, cellulose, hemicellulose and extractive substances, varies between solid and liquid forms, which affects the assessment of energy potential. The high cellulose content, which mainly comes from plant and fruit parts, underlines the potential of food waste for energy conversion. HTC for charcoal production depends on process parameters such as pressure, temperature and the ratio of biomass to water, with temperature having the greatest impact on product yield. Higher temperatures favor liquid and gaseous products over solid carbonaceous charcoal, as shown in Table 4 [30].

In studies on the HTC of food waste, temperature plays a decisive role in changing the quantities of volatile substances. Elevated temperatures reduce the volatiles and increase the amount of fixed carbon and ash, resulting in a higher carbon content in the carbonaceous coal. As mentioned above, the effect of temperature varies depending on the type of food waste due to its different chemical composition and thermal stability. Optimal temperature selection is critical to maximize the carbon content depending on the intended use, as found in various studies [30].

In addition, hydrodynamic cavitation (HC) technology has shown distinct advantages in simplicity and cost-effectiveness at different stages, including water treatment, lignocellulosic biomass pre-treatment, food processing and emulsification [37].

Torrefaction, a thermal pre-treatment process carried out at 200–300 °C in an inert atmosphere, improves the properties of biomass by increasing energy density, improving ignition properties and reducing moisture content. It increases the ratio of carbon to oxygen (C/O) and carbon to hydrogen (C/H), improving combustion efficiency and biomass storage. While the energy yield exceeds the mass yield due to the loss of volatile compounds, torrefaction significantly densifies the biomass and increases its energy content. During this process, the removal of oxygen produces gaseous compounds containing carbon, oxygen and hydrogen, which are crucial for reducing heat content and enabling the conversion of biomass into a solid fuel like coal. In addition to carbonization, torrefaction offers a way to produce solid fuels for heat and power generation, which underlines its importance for energy production [38].

Torrefaction is like pyrolysis and carbonization. The essential difference between pyrolysis, carbonization and torrefaction lies in their production objectives. The main objective of pyrolysis is to maximize liquid production while minimizing char yield. In carbonization, the objective is to increase the fixed carbon content and reduce the hydrocarbon content of the solid product, while in torrefaction, the objective is to increase the solid biochar content with specific atomic ratios (O/C) and (H/C) [36]. For electricity generation, torrefied biomass is used either alone or in combination with coal, which reduces the need for large quantities of coal. Different tests were performed to determine the moisture content (MC), ash content (ash), volatile matter content (VM) and fixed carbon content (FC) of different biomasses. These tests provide a basis for comparing how raw or torrefied biomass performs compared to coal in energy production. The volatile matter content of raw biomass before torrefaction is typically high, ranging from 70 to 88% by weight, while the fixed carbon content is low, ranging from 10 to 21% by weight. After torrefaction, the composition of VM (and MC) in the biomass decreases, resulting in an increase in the FC composition. The VM content of torrefied biomass is approximately 40 to 85 wt.%, while the FC content is 13 to 45 wt.%. Some authors use the FC/VM ratio to analyze the degree of torrefaction of biomass. The value of the atomic ratio increases with increasing torrefaction temperature as the FC content increases, while the VM content decreases after torrefaction. Based on the values investigated above, raw biomass has an FC/VM ratio of 0.14 to 0.24, while torrefied biomass has an FC/VM ratio of 0.33 to 0.53 [38].

Chen et al. reported on the volatile matter (VM) content in raw biomass before torrefaction. Research results showed that VM content is typically high, ranging between 70 and 88 mass%, while its fixed carbon (FC) content is usually low, ranging between 10 and 21 mass%. After torrefaction, the composition of VM (and moisture content, MC) in biomass decreases, resulting in an increase in the FC composition. The volatile matter content in torrefied biomass is approximately in the range of 40 to 85 mass%, while the FC content ranges between 13 and 45 mass% [39].

Nhuchhen and Basu, along with some other researchers, utilized the FC/VM ratio for the analysis of torrefaction extent in biomass. The ratio should increase with the increase in torrefaction temperature since the FC content increases, while the VM content decreases after torrefaction [40].

5. Conclusions

Considering the prevailing energy crisis and escalating pollution, there is an urgent need for research efforts aimed at promoting cleaner production through the exploration of environmentally sustainable energy sources. Central to this endeavor is the compelling challenge posed by excessive food waste, a prominent global problem facing humanity. This paper presents the results of investigations exploring various thermodynamic processes to convert food waste into valuable products with significant energy potential, representing a remarkable advance in the field. Careful research and analysis have shown that food waste, especially that with a relatively high moisture content, has a relatively low energy value, typically around 14 MJ/kg. Consequently, most food waste cannot be used as a renewable fuel source without pre-treatment by pyrolysis, torrefaction or hydrothermal carbonization.

According to Ipiales et al., hydrochar as a solid product contains approximately 40–90% of the initial carbon from the raw material and includes energy values ranging from 15–30 MJ/kg [41].

All processes, pyrolysis, torrefaction and hydrothermal carbonization are recognized techniques used to optimize the energy potential of food waste by reducing the atomic H/C and O/C ratios, thereby increasing the calorific value and enabling better solid fuel production. The post-pyrolysis results show significant differences in the yield of the different food waste categories, with meat/fat having the lowest yield (3.4%) and egg waste having the highest char value (50.52%). This indicates that biomass with a low char yield can be converted into gasses or bio-oils after pyrolysis. In addition, oily wastes prove to be particularly suitable for pyrolysis as they have a high energy yield and minimal operating costs associated with carbon management.

An advantage of torrefaction is that it allows for precise measurement of biomass weight loss during the process [42].

The concept of fuel ratio, expressed as the predefined ratio of carbon to volatile matter (FC/VM), is proving to be a key benchmark for evaluating the fuel potential of food waste and offers insights into its suitability as a substitute for charcoal or coal. The effectiveness of hydrothermal carbonization (HTC) as a transformative technology for food waste conversion is underappreciated as it demonstrates its versatility in processing plant and animal waste into products like biofuels. HTC is proving to be a viable way to produce solid fuels from wet and low-grade biomass, complemented by pyrolysis, which excels in the production of bio-synthetic fuels from high-energy biomass. Torrefaction, which takes place by controlled heating in a non-oxidative atmosphere at 200 to 300 °C, is characterized by its ability to remove moisture and volatile compounds to produce an energy-rich fuel.

A review of the recent literature indicates that torrefaction is a highly promising technique for enhancing the efficiency of biomass for energy utilization. Despite numerous studies conducted, there still remains a wealth of information on torrefaction that is not adequately identified and researched in detail [42].

As mentioned in the introduction, the novelty of this study lies in the fact that there is a lack of research on different types of food waste for the presented thermodynamic process. Our future work will focus on exploring this area further.

In summary, the results and research of this study highlight the promising potential of thermodynamic processes such as pyrolysis, torrefaction and hydrothermal carbonization in converting food waste into valuable energy sources.

Author Contributions: Conceptualization, methodology, validation, investigation, formal analysis, writing—original draft: A.Š.; formal analysis, writing—review and editing, supervision: D.G.; writing—review and editing, supervision: D.U. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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