energies

Review

An Extensive Review and Comparison of Modern Biomass Torrefaction Reactors vs. Biomass Pyrolysis—Part 1

Piotr Piersa *, Hilal Unyay, Szymon Szufa *, Wiktoria Lewandowska, Remigiusz Modrzewski, Radosław Ślężak and Stanisław Ledakowicz *

Faculty of Process and Environmental Engineering, Lodz University of Technology, Wolczanska 213, 90-924 Lodz, Poland; hilal.unyay@dokt.p.lodz.pl (H.U.); 238611@edu.p.lodz.pl (W.L.); remigiusz.modrzewski@p.lodz.pl (R.M.); radoslaw.slezak@p.lodz.pl (R.Ś.)

* Correspondence: piotr.piersa@dokt.p.lodz.pl (P.P.); szymon.szufa@p.lodz.pl (S.S.); stanislaw.ledakowicz@p.lodz.pl (S.L.); Tel.: +48-60-940-7525 (P.P.); +48-60-613-4239 (S.S.); +48-42-631-3715 (S.L.)

Abstract: Major efforts are currently being made in the research community to address the challenges of greenhouse gas emissions from fossil fuel combustion by using lignocellulosic biomass, agricultural waste, and forest residues as cleaner energy sources. However, its poor qualities, such as low energy density, high moisture content, irregular shape and size, and heterogeneity, make it impossible to utilize in its natural state. Torrefaction, a simple heat treatment method, is used frequently with natural bioresources to improve their thermal characteristics so that they may be used as energy sources in domestic power plants. The quality of the resulting torrefied solids (biochar) is determined by the heat condition settings in the absence of oxygen, and it may be enhanced by carefully selecting and altering the processing parameters. The comprehensive overview presented here should serve as a useful toolkit for farmers, combined heat and power plants, pulp and paper installations, and other industrial plants that use biomass as a substrate for biofuel production. This research focuses on torrefaction product properties, reaction mechanisms, a variety of technologies, and torrefaction reactors. It is impossible to determine which torrefaction technology is superior as each reactor has unique properties. However, some suggestions and recommendations regarding the use of torrefaction reactors are given.

Keywords: torrefaction; pyrolysis; biochar

check for updates

Citation: Piersa, P.; Unyay, H.; Szufa, S.; Lewandowska, W.; Modrzewski, R.; Ślężak, R.; Ledakowicz, S. An Extensive Review and Comparison of Modern Biomass Torrefaction Reactors vs. Biomass Pyrolysis—Part 1. *Energies* **2022**, *15*, 2227. https://doi.org/10.3390/en15062227

Academic Editors: Emmanuel Revellame and Randy Maglinao

Received: 7 February 2022
Accepted: 13 March 2022
Published: 18 March 2022

1. Types of Thermochemical Processes, Pyrolysis-Torrefaction

1.1. General Knowledge and History of Thermochemical Processes

This work aims to solve problems related to the use of specific types of biomass waste as a biofuel or valuable biochar processed through torrefaction or pyrolysis. Farmers occupy an important position in the food industry. After the harvest period, most farm stubble goes up in flames which leads to air pollution; 92 million tons of agricultural waste is burned each year in India alone. Burning biomass in the open accounts for around 18% of CO_2 emissions worldwide [1]. To solve this problem and create a new revenue source for farmers, the authors propose a new technology that will be examined in this work. The aim is to describe possible kinds of torrefaction and pyrolysis reactors where farmers might sell their waste to industrial customers instead of burning it. It may even be possible for them to build semi-pilot installations depending on the waste type. The authors believe it will be possible to create a circular process between biofuel producers and farmers which would be attractive for both sides. Thermochemical conversion processes for biomass differ according to reaction temperature and oxygen present. With the exception of combustion, the processes allow for valuable products such as biochar, bio-oil, and syngas. Gasification products mainly comprise syngas and less bio-oil [1]. One of the most well-established and commonly utilized thermochemical methods is combustion. Direct biomass combustion and boiler combustion are two common methods found in the industry. In general, the combustion efficiency of a stove ranges from 10% to 25%. However, boiler combustion has a significantly greater thermal efficiency of 70% to 80%, making it more appropriate for large-scale heat and power generation applications. In terms of combustion modes, biomass-fueled boilers are classified as traditional stoker-fired boilers and fluidized-bed boilers [2]. Gasification is a thermochemical degradation process that produces syngas (also known as producer gas, product gas, synthetic gas, or synthesis gas) through interactions between the fuel and the gasification agent. The syngas consists mainly of CO, H_2, N_2, CO_2, and minor hydrocarbons (CH_4, C_2H_4, C_2H_6, etc.). H_2S, NH_3, and tars may also be present in trace concentrations [3–5]. Gasification is one of the preferred methods in producing hydrogen as an energy carrier [6]. Liquefaction is when a granular material transitions from a solid to a liquefied state due to increasing pore-water pressure. Liquefaction can occur in sediments because more dense material is deposited on top of less dense sediment through a density inversion [7]. Pyrolysis is the process of biomass decomposing under anaerobic circumstances at temperatures ranging from 400 °C to 900 °C. This thermal decomposition leads to compounds of simpler structure (with lower molecular weight) or to elements. The resulting pyrolytic products are a gaseous substance (syngas), a liquid (tar), and char, with ash as an unwanted residue [8].

- Gaseous fraction: non-condensing gases (NCG) that primarily comprise hydrogen, methane, carbon monoxide, carbon dioxide, and other gases in lower quantities.
- Liquid fraction: tars and/or oil and substances such as acetic acid, acetone, and methanol.
- Solid fraction: mainly pure carbon with some inert substances.

It should be noted that the proportion of these individual fractions depends on the temperature, residence time in the reactor, pressure, and turbulence, as well as the properties of sewage sludge (pH, organic matter content, and dry matter content). Decomposition products include pyrolysis gas which can be used as a type of fuel, and coke or oil which can also be used as raw materials in the chemical industry. The pyrolysis process can be tested by thermogravimetry (TG), differential scanning calorimetry (DSC), and additionally, by mass spectrometry (MS) and chromatographic techniques [9]. The mechanism of the process can be identified with the help of these methods. Pyrolysis can be carried out by various methods and under different process conditions. Pyrolysis is considered an endothermic process from the thermal effect point of view. The heat may be supplied in a diaphragm fashion, where the reactor is heated with flue gas, or by a heat carrier such as a heated catalyst, an inert carrier (hot sand), resistance heated reactor elements, or by friction heating of the material. The process parameters (residence time, heating rate, process temperature, and input material) determine the composition and quantity of individual fractions of the products obtained.

Types of pyrolysis are mainly characterized as slow, fast, flash, and microwave pyrolysis depending on heating rate, residence time, and pyrolysis temperature. Pyrolysis results and conditions are shown in Table 1. In the case of fast and flash pyrolysis, a different structure of the reactors is required due to the specific features of the process that are aimed mainly at the production of bio-oil, or a greater share of energy gaseous products than in the case of slow pyrolysis (carbonization/torrefaction).

The fundamental characteristics of the fast/flash pyrolysis process are the following.

- Very high heating rates (~1000 °C/min) and heat exchange, which require a supply of raw material with a high degree of fragmentation (less than a few mm);
- Carefully controlled temperature in the gas phase reactor (approx. 500–650 °C);
- Short residence times, usually less than 2 s;
- Rapid cooling of gaseous pyrolysis products, leading to bio-oil as a key ingredient.

The particle size greatly influences the heating rate of the solid, and thus the residence time in the reactor and the proportion and composition of individual product fractions. The research showed that in the case of larger particles, lower yields of liquid products were observed, which may be the result of the effect of grain size on the course of secondary reactions of gaseous products within the solid phase. In the experiments carried out in the fluidized bed, it was found that the increase in the particle size from 53–63 μm to 270–500 μm led to a decrease in the emission of tars from 53% to 38% in the proportion of fuels obtained from biomass. It was shown that the maximum release of bio-oil (58% of biomass input mass) was obtained at a temperature of 500 °C with a particle size of 212–425 μm. The implementation of the technological conditions of flash pyrolysis, aimed at producing bio-oil, therefore requires a high degree of comminution of the raw material compared to other pyrolysis methods. However, the smaller particle size of the biomass required increases the cost of raw material preparation. By reducing the particle size from 2.5 mm to 250 μm, the raw material preparation costs increase from USD 1.80/ton to USD 5.60/ton, respectively. The heat required to raise the biomass temperature to the temperature required for the fast pyrolysis reaction and its initiation is in the order of 1–2 MJ/kg of biomass containing 10% moisture [10,11].

As shown in Figure 1, torrefaction is a thermal treatment process derived from slow pyrolysis at low temperatures of 200–300 °C in the absence of oxygen conditions. During the torrefaction process, the structure of the biomass changes in such a way that the material becomes hydrophobic and more brittle. Even though weight loss is 30%, the energy loss is only 10%. Storage of such material is easier compared to fresh biomass since biodegradation and water uptake are minimized due to the hydrophobic properties of the material after torrefaction. Torrefaction is also used to improve the properties of wood intended for construction purposes. During the process, flammable gas is released, which is used to balance the heat balance of the process. The biocarbon obtained as a result of torrefaction can be used for energy purposes, but also in agriculture, as it is a valuable material that enhances the value of the soil.

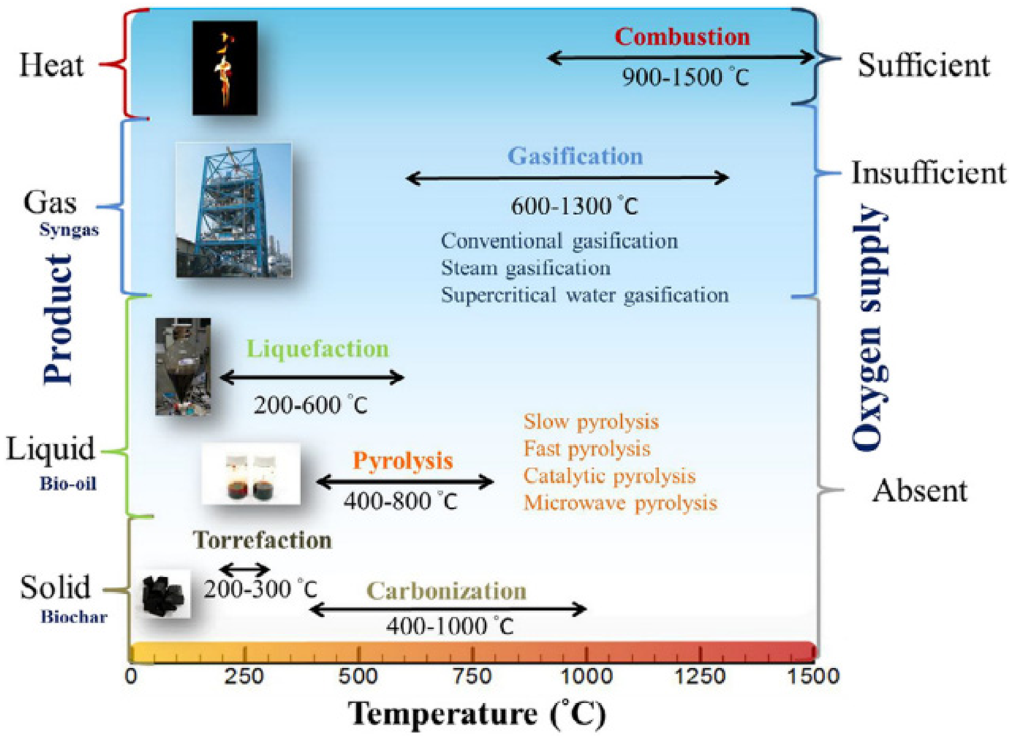

Figure 1. Thermochemical conversions of biomass [12].

Table 1. Pyrolysis types depending on operation conditions and products [3,13].

Pyrolysis	Operating Conditions	Results
Slow pyrolysis	Temperature: 300–700 °C Vapor residence time: 10–100 min Heating rate: 0.1–1 °C/s Feedstock size: 5–50 mm	Bio-oil: ∼30 wt% Biochar: ∼35 wt% Gases: ∼35 wt%
Fast pyrolysis	Temperature: 400–800 °C Vapor residence time: 0.5–5 s Heating rate: 10–200 °C/s Feedstock size: <3 mm	Bio-oil: ∼50 wt% Biochar: ∼20 wt% Gases: ∼30 wt%
Flash pyrolysis	Temperature: 800–1000 °C Vapor residence time: <0.5 s Heating rate: >1000 °C/s Feedstock size: <0.2 mm	Bio-oil: ∼75 wt% Biochar: ∼12 wt% Gases: ∼13 wt%

1.2. Torrefaction Background

Torrefaction started to be used at the beginning of the industrial revolution, although it did not receive very much attention. The first torrefaction process patents were filed by Thiel (1897) and Offrion (1900) in the late 19th century and ended with the development of the coffee industry and its roasting process [14]. The first published work on drying and torrefaction theory belongs to Hohn of Germany in 1919 [15]. In the 1930s, there were still insufficient resources dedicated to producing gaseous fuels, although some research on torrefaction was carried out. In the first half of the 20th century, work devoted to the torrefaction of biomass for energy appears only occasionally [16]. Rather, this period is recognized for increased knowledge and fundamental data on thermal lignocellulosic materials treatments, exceptionally high-temperature drying, dry distillation, thermal degradation, pyrolysis, thermal stabilization, and wood preservation. Early pioneering research was undertaken by Arjona et al. and Bourgois et al. between 1979 and 1989 [17,18], and large-scale work continues to be performed by many scientists and engineers from the Eindhoven University of Technology and the Dutch Center for Energy (ECN) [19]. Arjona et al. published the first academic publication on the torrefaction of coffee in 1979, which presented the first practical implementation of the process [18]. Early work in France resulted in a demonstration unit in the late 1980s when the torrefaction process was used to manufacture a reducing agent for the metal sector. The company Pechiney developed a torrefaction unit, which ran for a few years until it was shut down for economic reasons. It should be noted and acknowledged that additional scientific activity was carried out throughout this period in addition to the French and Dutch studies. By the early 21st century, eight publications in total had been published in France, Germany, Brazil, the USA, and Thailand [15,18,20–25]. At the time of writing, a search for the word ‘torrefaction’ in the Web of Science (WOS) data collection yielded 2817 results. This indicates that torrefaction research substantially started after the 2000s, except for the previous eight works mentioned. However, when compared to research on biomass pyrolysis, papers on torrefaction account for just 2% of the total number of studies published.

1.3. Various Types of Torrefaction

According to types of utilization, the definition of torrefaction is commonly associated with roasting, mild pyrolysis, slow pyrolysis, and thermal pretreatment [26–28]. Low calorific value, bulky structure, difficulties in transportation, low energy density, and non-homogeneous structure of raw materials such as agri-biomass present some issues for biomass in terms of fuel usage [29]. Torrefaction of biomass addresses this handicap and allows homogeneous carbonized high energy density biomass to be obtained. In Table 2, raw biomass properties that may be problematic in use as a direct source of energy production are identified [30]. Torrefaction changes the physical and chemical properties of biomass. It decreases undesirable features such as volatile matter, moisture content, H/C and O/C ratio, hygroscopicity, and the biological degradation of biomass while increasing mass density, calorific value, and grindability.

Table 2. Raw and torrefied biomass profile.

Raw Biomass Property	Advantages of Torrefaction for Biomass	Refs.
High moisture content	Decreases the moisture. The hydrogen released increases H_2 into syngas at gasification.	[31]
High H/C and O/C ratio	Leads to higher energy density at biomass (van Krevelen diagram). Deoxygenation and dehydrogenation occur relatively higher than decarbonization, leading to higher carbon density.	[32]
High biological degradation	Following torrefaction, significant breakdown of hemicelluloses, widely regarded as a critical nutrient for the development of wood-rotting fungi, leads to an increase in biomass durability.	[33]
High hygroscopicity	Increases hydrophobicity. Torrefied biomass has 35% less equilibrium moisture content (EMC), leading to long storage, less moisture, and decomposition risk.	[34]
Low calorific value Low mass density	Torrefaction is, therefore, used to remove unwanted components (H and O) from biomass, yielding calorific values similar to coal (25–35 MJ·kg^{-1}).	[35]
Poor grindability	Cell walls get destroyed, and pores become the complete result of volatile matter reduction. Torrefaction increases biomass grindability, which is essential for further applications.	[36]

The weight loss of biomass during torrefaction is caused mainly by the degradation of its hemicellulose elements. The hemicellulose component degrades most within the 200 to 300 °C temperature range, as seen in Figure 2. The wall component of biomass, lignin, begins softening beyond glass-softening temperature (around 130 °C), which aids the pelletization of torrefied biomass. Unlike hemicellulose, cellulose undergoes only little devolatilization and carbonization, which does not begin below 250 °C.

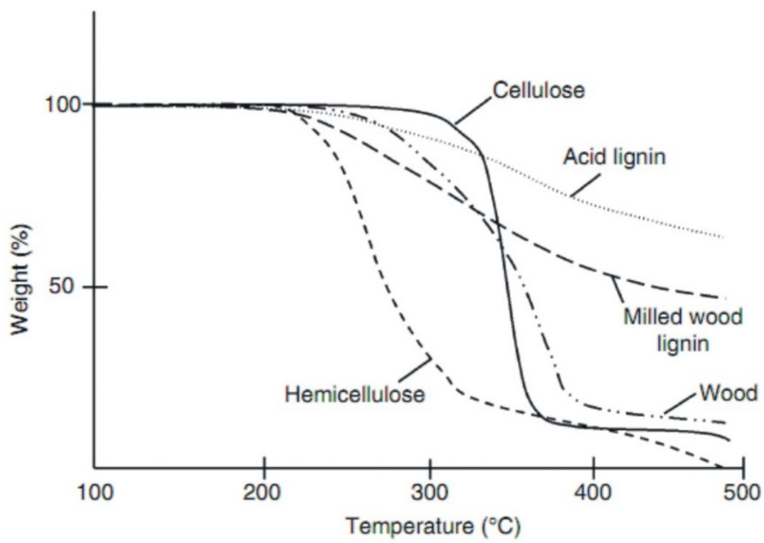

Figure 2. Weight loss in wood cellulose, hemicellulose, and lignin during torrefaction (TGA analysis). Reprinted with permission from ref. [37]. Copyright 1971 Elsevier.

In Figure 3, the van Krevelen diagram shows biomass in the upper-right corner of the figure, but torrefaction shifts it closer to the medium range through to coal. It occurs because of a decrease in the O/C and H/C ratios. The H/C and O/C ratios (atomic ratios) serve as indicators for the degree of carbonization of biomass [38]. Grycova et al. (2020) and Granados et al. (2016) clearly found in their work that increasing the temperature enhances the quality of the material. When the temperature reaches 300 °C, the result seems closer to lignite. This is because cellulose and hemicellulose degrade extensively during torrefaction, resulting in a higher energy density substance [39,40].

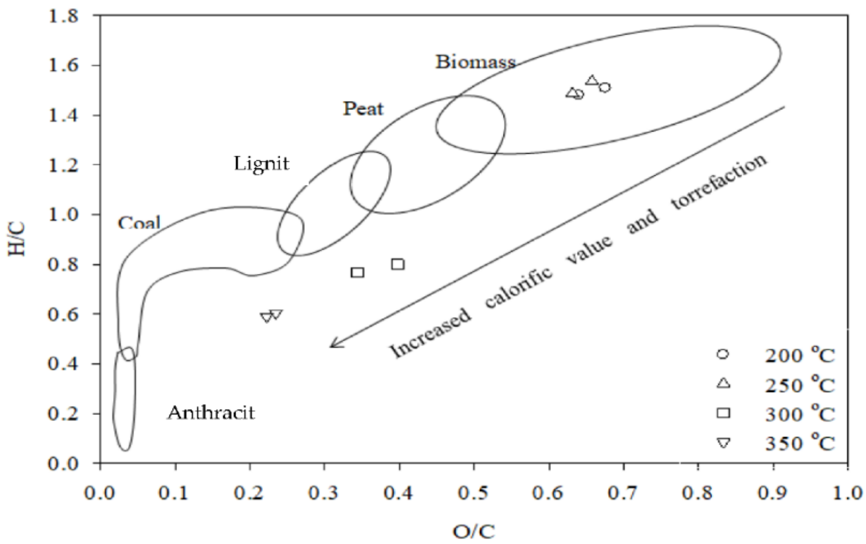

Figure 3. The van Krevelen diagram for fuels [41].

Torrefaction is classified in three ways, dry, wet, and steam torrefaction, and the latter is further classified according to oxidative, non-oxidative, with water or dilute acid [42]. Figure 4 shows the classification of torrefaction.

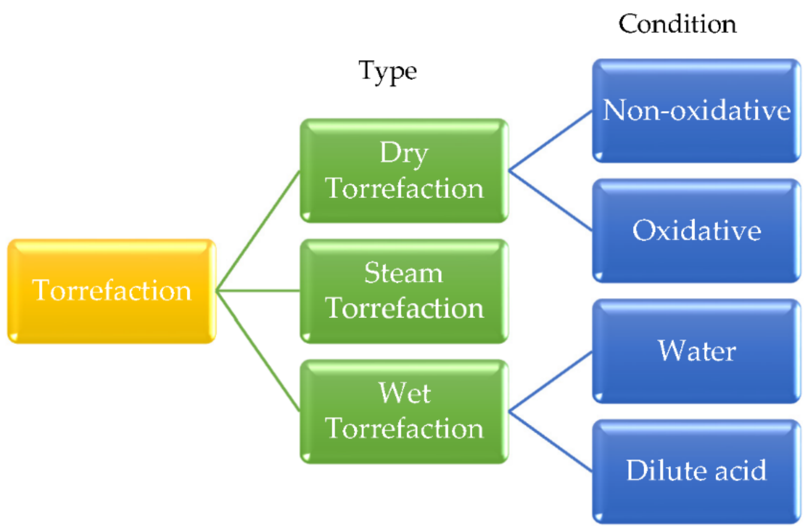

Figure 4. Classification of torrefaction.

Dry torrefaction: This is sometimes referred to as a mild pyrolysis (200–300 °C) process, implying that the thermal degradation occurs at a low temperature and under inert circumstances. It can be under oxidative or non-oxidative conditions, with oxygen or air as carrier gas. Oxidative torrefaction has a faster response rate than non-oxidative torrefaction due to the presence of oxygen and the exothermic reactions that occur during thermal degradation [43]. As nitrogen removal from the air is unnecessary when utilizing air or flue gas in biomass torrefaction, this may minimize operational expenses [44]. The fuel qualities of biomass torrefied by a sweep gas with low oxygen concentrations (<6 vol %) are similar to those of nitrogen torrefied biomass. Nevertheless, oxidative torrefaction has a lower efficiency than non-oxidative torrefaction. Acharya et al. demonstrated that when torrefied at 300 °C, torrefied biomass's higher heating value (HHV) reduces with rising oxygen content [42].

Wet torrefaction: This is another torrefaction option where the biomass is torrefied under pressured water. Compared to dry torrefaction, the pressure is strong enough to retain the water in liquid form, and lower temperatures are required. Wet torrefaction is a process that can be carried out in subcritical water at temperatures ranging from 180 to 260 °C and pressures of up to 5 MPa, yielding three products: gas, aqueous chemicals, and solid fuel. The biomass species, treatment temperature, and duration significantly impact product distribution [45]. During wet torrefaction, the hemicellulose in biomass is hydrolyzed and depolymerized, yielding monomers and oligomers with minimal influence on lignin, which results in less moisture content biochar than in the input biomass [46–48]. The liquid effluent of the wet torrefaction process is water containing alkali chemicals, which provides an environmental challenge in discharging the processing water that has not been addressed in wet torrefaction research investigations to date [49]. Table 3 highlights and tabulates the relation between dry and wet torrefaction.

Table 3. Dry and wet torrefaction properties.

Properties of Torrefied Biomass	**Dry Torrefaction**	**Wet Torrefaction**		**Refs.**
		Vapor Water	**Liquid Water**	
Hydrophobic	Yes	Yes	Yes	[42,50]
Content of moisture	Lower	Higher	Higher	[51,52]
Heating value	Lower	Higher	Higher	[42,50]
Bulk density	Low	Low	Low	[53,54]
Storage at open atmosphere	Possible	Possible	Possible	[42,50]
Purity of the product	Medium	High	High	[42,50]
Grindability	High	High	High	[53,54]
Product type	Gas, tar, solid	Solid, gas, liquid	Solid, gas, liquid	[42,50]
Applications	Fuel and char	Fuel and char	Fuel and char	[51,55,56]
Carbon contents	Low	Medium-high	High	[42,50,51]

Super-heated steam torrefaction: This is the latest invention concerning the torrefaction process. As a pretreatment, using super-heated steam opens the fibers and makes the biomass polymer more accessible for subsequent operations such as fermentation, hydrolysis, or densification. As a result, super-heated steam is a beneficial and necessary technique for improving the recovery of sugars and other essential biomass components. Resulting materials have advantages such as high heating value (HHV), minimal moisture absorption, and superior pelletizing qualities [57]. Another advantage of the process is that there is no need for nitrogen or flue gas expenses as in a carrier such as dry torrefaction. Super-heated steam torrefaction is a process on which only a few studies have been carried out so far [58,59].

2. Review of Different Torrefaction Technologies

2.1. Initial List of Available Technologies on The Market

Torrefaction is typically performed at temperatures ranging from 200 to 300 °C, with the temperature remaining constant for 15–60 min. It is critical for cost-effective biomass treatment in the selection of precise values for these two main parameters for different types of biomass [60]. Due to the substrate's heating, the reactors can be divided into two main groups, those with indirect and direct heating methods. Indirectly heated reactors can be divided into rotary and screw (auger) reactors. On the other hand, direct heating reactors can be further divided into these three subgroups due to the oxygen content in the heating medium.

- Reactors in which the heating medium does not contain oxygen,
- Reactors in which the heating medium contains a small amount of oxygen,
- Other.

The first machines include a screw conveyor, rotary, microwave, vibrating, stepped, belt conveyor, and moving bed reactors (Table 4). This group of reactors is used most often.

Table 4. Torrefaction reactor types [60].

Torrefaction Reactors			
Direct Heating			**Indirect Heating**
Oxygen Free Heating Moving Bed Multiple Zones Drum	Low Oxygen Heating Augur Moving Bed Entrained, Spiral	Other Fluidized Bed Microwave Hydrothermal	Augur Rotary Drum

The torrefaction reactors differ mainly in solution types related to the following.

- Material flow;
- Heating mechanism of the substrate;
- Heat source;
- Torgas treatment [61].

Each type of reactor has its pros and cons. Some of the solutions are not expensive and are easy to build and operate. Some exhibit difficulties related to material flow and heat transport, which contribute to the uniform heating of the substrate. Some proposed devices work well on a laboratory scale, while others on an industrial scale. However, at this stage of waste torrefaction technology development, it is difficult to recommend a suitable reactor type unequivocally [62]. As the torrefaction process is carried out through many different methods and using various solutions of heat transfer and biomass conversion technology, an in-depth analysis of the available solutions on the market was carried out, along with their advantages and disadvantages.

(1) Rotary drum reactor

This uses a drum to torrefy the biomass under an inert gas atmosphere. The technology is widely used in a variety of biochar pilot plant configurations. Heat can be applied directly or indirectly in the rotary drum. The hot gases are passed through the reactor drum using the direct heating method. Heat is provided to the reactor and biomass indirectly by passing gases through the reactor shells [63]. The disadvantage of the rotating reactor drum is that it is difficult to scale (when the size of the reactor becomes too large, scaling is complex because the area of heat transfer to biomass during carbonization is limited) [63,64]. Other disadvantages of this type of reactor are the relatively high cost and the process temperature that is difficult to control [65]. However, companies that develop this technology say there is a solution. To better understand how the rotary drum reactor works, it is worth looking at the photo in Figure 5.

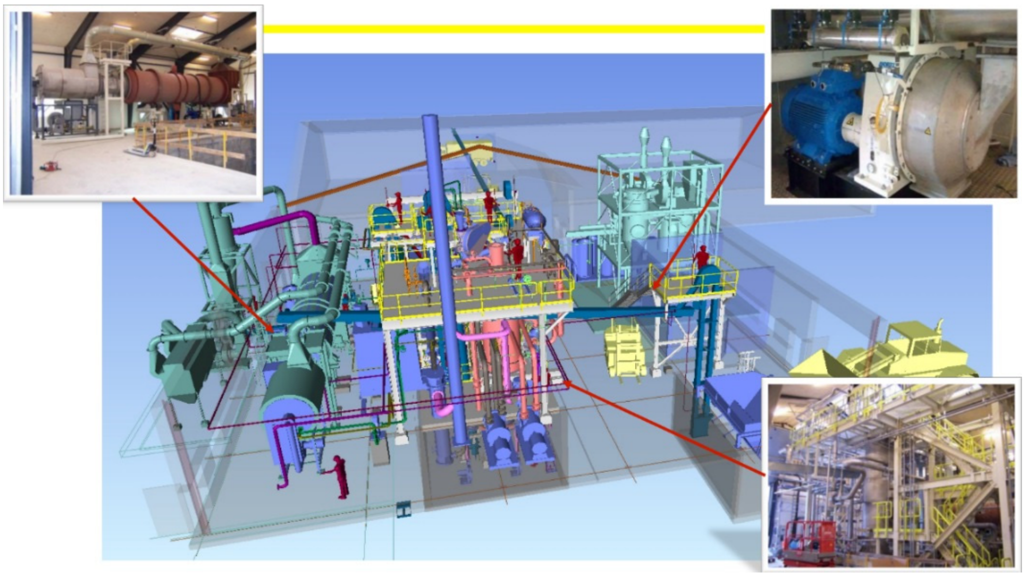

Figure 5. Completed installation with a rotary drum reactor for biomass torrefaction by company ANDRITZ AG. Reprinted with permission from refs. [66,67]. Copyright 2013 VTT.

(2) Moving bed reactor

Heat can be applied directly or indirectly to woody biomasses [68]. The moving bed is small and basic in structure, with a high heat transfer rate, precise temperature control, good product quality, flexibility when fueling with a specific fuel, and low investment costs [55]. The disadvantage of moving a bed reactor is that when the scale is reached in the reactor, the situation can become dangerous due to the pressure and the possibility of damaging the main body of the reactor. The pressure drop also affects the particle size of the biomass that is to be used in the moving bed. Another issue in the indirect heating version concerns non-uniform heat distribution [65].

Andritz and ECN have a pressurized torrefaction reactor design with a 700,000 ton/year capacity. As seen in Figures 6 and 7, the reactor includes both a multiple heart furnace and moving bed with a two-stage cross-flow-current, followed by counter-current heating from the bottom. A demo plant in Stenderup, Denmark, has been set up with 1 ton/h [69]. This example of a continuous reactor consists of a closed reactor in which the feed inlet at the top progressively goes lower as the process continues. There is a possibility that the carrier will accumulate in the channels, the heat transfer medium through the bed, leading to an uneven distribution of the product at the bottom of the reactor, caused by a lack of sufficient mixing of the biomass. However, this risk has not yet been observed in plants with a capacity of 100 kg/h: the risk increases in reactors with higher capacities. The filling degree of the moving bed is relatively higher compared to the design of the Torbed type reactors, for example, since the entire volume of the reactor is used for the carbonization process. The pressure drop in the moving bed is relatively high, especially when treating is of small size (<5 mm). This can be partially avoided by screening the input material. However, the formation of smaller particles inside the reactor cannot be avoided, especially in the lower part where the pressure is highest.

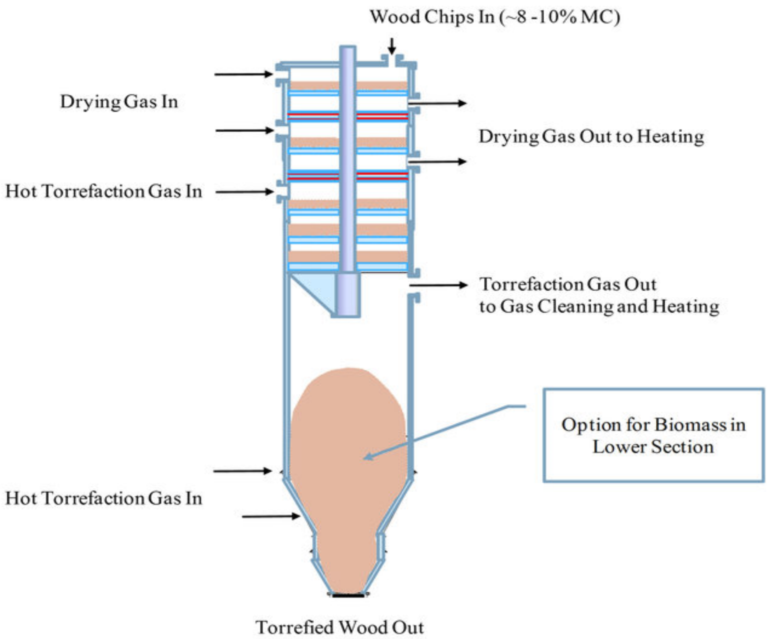

Figure 6. A reactor for torrefaction with a moving bed [66,70].

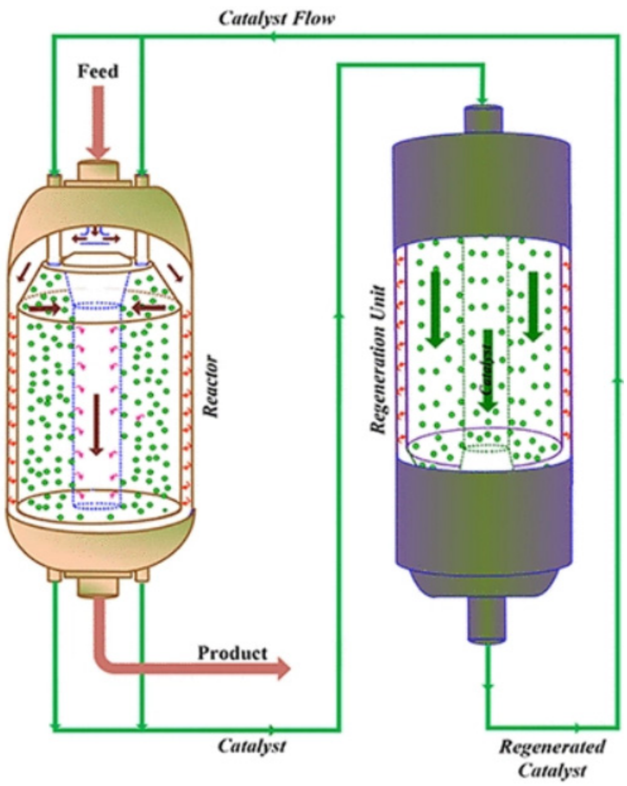

Figure 7. Scheme of operation of a moving bed reactor. Reprinted with permission from refs. [66,71]. Copyright 2019 ACS.

The technical limitations so far enable the formation of vertical "tunnels", increasing the efficiency of heat treatment along the diameter of the reactor due to a change in the size of the raw material particles. Figures 7 and 8 show the moving bed reactor, and operational and process overview schematic visuals.

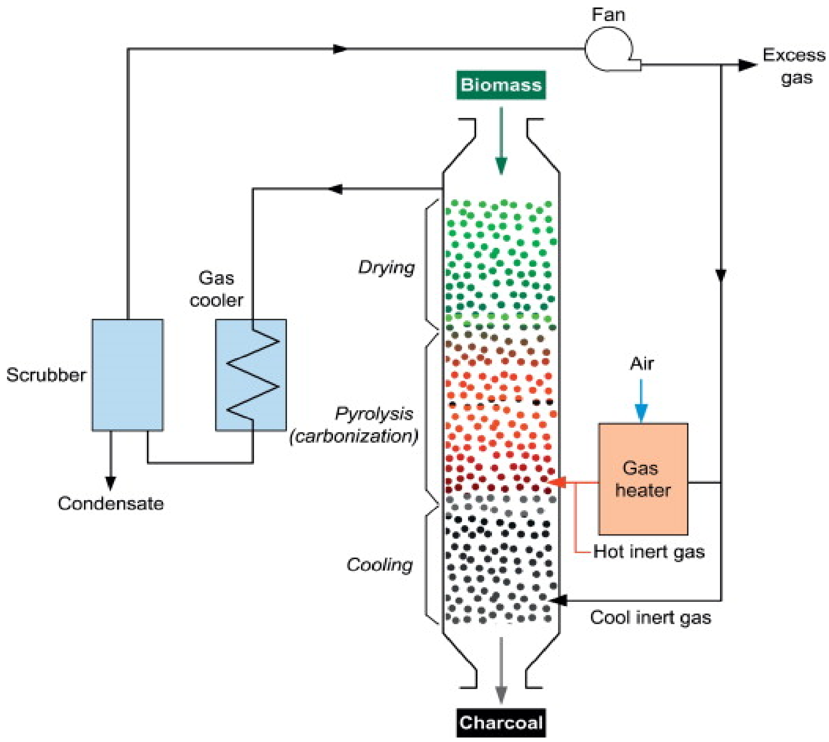

Figure 8. Schematic overview of the process. Reprinted with permission from ref. [72]. Copyright 2015 Elsevier.

(3) Screw (Auger) reactor

In a screw reactor (shown in Figures 9 and 10), the screw pushes the biomass forward through the twisted screw of the reactor. A reactor used in the Pechiney process uses a screw reactor, one of the first facilities to be designed for the torrefaction process. An indirectly heated reactor is heated by a separate boiler with oil [73]. These types of reactors ensure process continuity and are compact in design. A screw reactor's limitations include difficulties in scaling up and low energy efficiency (60–80%). The reactor also requires biomass with low moisture content since the size of the reactor determines the heat load needed, and for design reasons, they have limited heat transfer. In the case of high temperature, a low moisture content (about 5–7% w/w) is mandatory as the reactor would not be able to reach the required process temperature otherwise [73].

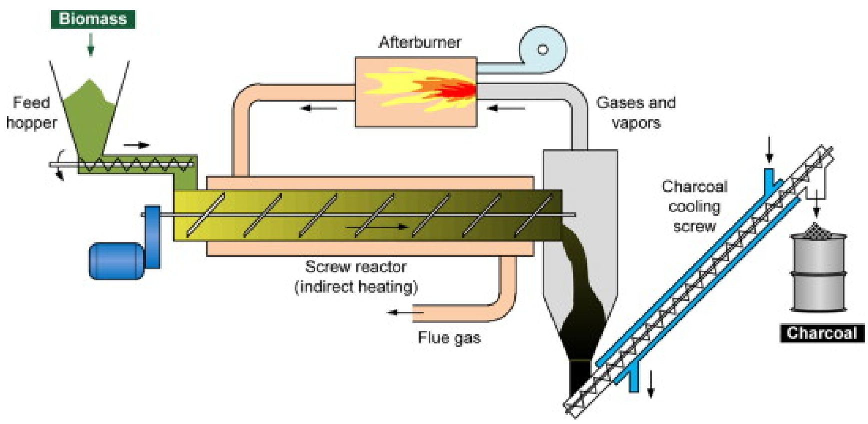

Figure 9. Simplified system of a torrefaction process with screw reactor (here indirectly heated) for charcoal production. Reprinted with permission from ref. [72]. Copyright 2015 Elsevier.

A screw reactor uses one or more screws to transfer biomass through the reactor and a continuous reactor. A screw reactor can be placed both vertically and horizontally and is often indirectly heated inside a hollow wall or a hollow screw. There are certain differences in the screw reactor design when the heat is supplied directly by the double screw mechanism. The development of carbon decolorizing in the hot zones is a drawback of indirectly heated reactors.

Furthermore, due to the restricted mixing of the biomass, the heat transfer rate in these reactors is limited. The retention time in the reactor depends on the length and rotational speed of the reactor. However, the buildup is not expensive and the scalability is restricted as size increases [74]. However, the highly efficient mixing of biomass with the hot medium is characterized by intense heat transfer, making large screw reactors highly efficient. The continuously rotating reactor drum can be considered a technology that has been proved in various applications. Torrefaction can be sped up or slowed down by adjusting the torrefying temperature, rotating speed, length of drum, and angle of drum. The rotation of the drum ensures homogenous biomass mixing, and the heat transfer is intense. However, the wall friction on the inside of the drum also increases the fine fractions. Drum rotation control affects limited scalability, and, therefore, it requires more modular power and configuration.

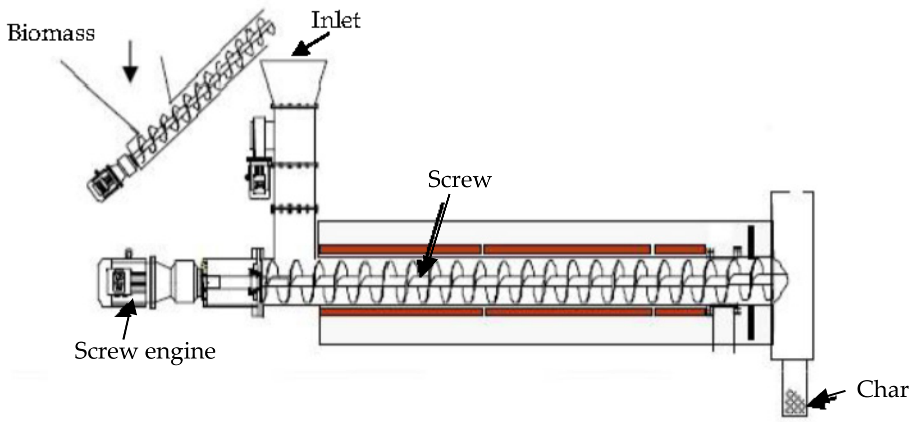

Figure 10. A layout of screw reactor [75].

(4) Multiple hearth furnace with vertical baffles

This is a cylindrical, refractory-lined furnace with a steel shell. It includes 6 to 12 horizontal fireplaces and a centrally rotating shaft with agitator arms [76]. Cooling air is sent into the shaft. The gas enters the first firebox and flows downwards, while the air is needed for combustion from the bottom to the top. The operational principle of this type of reactor is presented in Figure 11. An example of a shelf oven is the Wyssmont dryer, which was initially developed as a roasting device. The Wyssmont dryer is also often referred to as a turbo dryer. During torrefaction in the reactor chamber, the air is trapped in the outer shell, and steam super-heated with nitrogen is used in the recirculation of the atmosphere. Multi-module furnaces and stacks are easy to scale up, and reactors are produced from 4 to 35 feet in diameter [72]. The heat transfer surface of the tray furnace is efficient, but it is not easy to control the reactor temperature. One of the major drawbacks is that the reactor is large in size [65]. It is a continuous reactor consisting of several layers. It has been proven that this type of reactor is suitable for various applications. One phase of the torrefaction process takes place in each layer. The temperature gradually increases in each layer from 220 °C to 300 °C. The biomass comes out of the top of the reactor horizontally and is mechanically pushed inwards. It then falls through an opening in the plate on the second plate, where it is mechanically pushed outwards, then falls through another entrance, and so on. The process is repeated in multiple layers, resulting in even mixing and gradual heating. The heat is supplied to the individual inner layers of the reactor directly by gas burners and steam injection. In the upper layers of the reactors, the biomass is first dried, and torrefaction occurs in the lower layers.

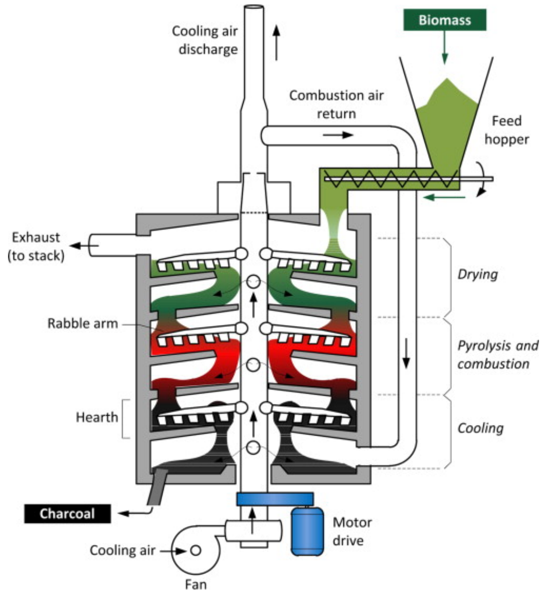

Figure 11. Schematic overview of the Herreshoff multiple hearth process. Reprinted with permission from ref. [72]. Copyright 2015 Elsevier.

This reactor can be scaled to a diameter of 7 to 8 m, resulting in a relatively low investment (expressed in EUR per ton/h of product) for large-scale installations (Figures 12 and 13). It uses burners in a natural gas system or special suspension burners for wood dust from the raw material produced. However, the use of natural gas to make the gas flow through the reactor contributes to an increase in moisture content overall, which causes a rise in the moisture content of the torrefied material. This may have an adverse effect on the increased moisture content and increase the post-extrusion stability of the granules. This technology can be used to process a more comprehensive range of particle sizes from sawdust to larger wood chips and even large-sized branches. The technology is also suitable for research into the individual steps in each sequence, as each step in the torrefaction process can be readily accessed for material and gas sample testing, fine adaptive control, and even additive injection temperature. The typical time for converting biomass to biochar is 30 min for top-down carbonization.

Figure 12. Examples of a multiple hearth furnace for forest biomass torrefaction process provided by the company Thermya. Reprinted with permission from refs. [67,72]. Copyright 2013 VTT.

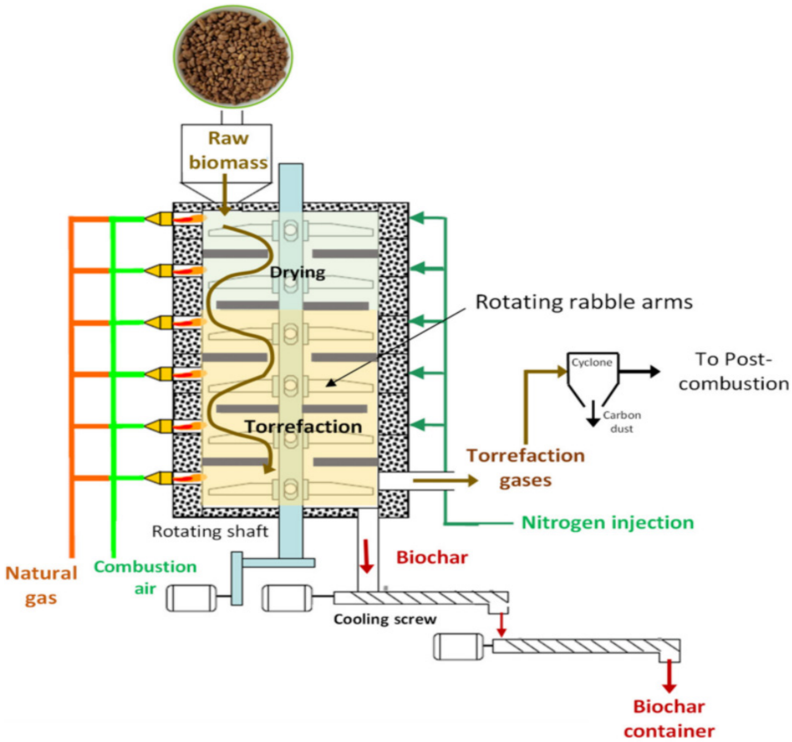

Figure 13. Visualization and cross-section of the multiple hearth furnace used for torrefaction of biomass in successive stages from top to bottom [77].

(5) Fluidized bed reactor

In a fluidized bed, the biomass in the bed is indirectly heated with hot steam. A great lifting force is needed to keep the biomass fluidized, and this method may not be possible with large particle sizes. Hence, the fluidized bed reactor is very sensitive to particle size: the size of the particles in the fluidized bed should not be too small because this leads to coagulation problems, and the ability to fluidize is limited by water. According to the manufacturers of fluidized bed reactors for the torrefaction process, typical particle size does not impede use in these reactors. The size of the biomass varies during torrefaction, making it difficult to control the fluidization behavior inside the reactor. Another major disadvantage of a fluidized bed reactor is the slow temperature response. Fluidized bed reactors have the advantages of good heat conducting properties, and they are good for scaling up to larger sizes [65]. In this torrefaction reactor, an inert gas is blown to the bed into the granular solid particles of the heat carrier in such a way that the solids behave like a liquid [78]. These hot particles are vigorously and successively agitated in a turbulent state: it is easy to heat all raw biomass particles so that they fall to the bottom of the reactor. Biomass particles subjected to the torrefaction process are in a well-mixed state, and the temperature distributions are uniform. Thus, this system provides a quasi-homogeneous product quality which is generally difficult to achieve in other reactors. The separation of bed material from the torrefied biomass is another limitation of this technology. Dhungana et al. were able to produce the proper slurry (without clogging the channels), at a biomass size range of 0–714 µm (with no other materials in the bed) [65]. The upside is that the system takes advantage of no permanent heat source needed: size limitation and entrainment of particles can then become an important issue. The dominant heat exchange method is that of particle-to-particle in a fluidized bed. Rapid heating to torrefying temperature can potentially increase reactor efficiency, but the effect of rapid heating of biomass on product quality has not yet been thoroughly studied. Figure 14 indicates the commercial version of the fluidized bed reactor by AIREX energy.

Figure 14. Fluidized bed reactor for the biomass torrefaction process by AIREX Energy. Reprinted with permission from ref. [79]. Copyright 2012 AIREX ENERGY.

(6) Torbed reactor

The Torbed® reactor was developed by Torftech Ltd. (Newbury, UK) in 1998 (Figures 15–17). In the Torbed reactor, the moving particle bed is dispersed, while the cyclone accelerates the biomass particles to a high velocity, and a gas stream with heat is delivered in a toroidal system. The Torbed reactor can only handle fine wood particles, resulting in fuel flexibility. The toroidal flow is created by injecting nitrogen with an average fluidization velocity of 50 to 80 m/s via the stationary angled blades. The required mixing and roasting times are from 90 s to 5 min at a temperature of 280 °C, which makes the yield of biochar product very high. However, carbonization becomes a risk due to high temperatures [80,81]. There are high turbulences and intense contact between the material and the process gas inside the reactor. This can be done by influencing the kinetics of the reaction, which increases the efficiency of the process, which in turn is why the duration of this process is so short. Moreover, Torbed reactors have a low-pressure drop, leading to high energy efficiency [82]. Torbed technology is widely used in a variety of applications, including combustion.

Installations with Torbed reactors have been built for continuous and discontinuous operation with diameters of 5 to 7 m (Figure 16). However, roasting using a Torbed has only been demonstrated discontinuously as a micro-scale installation (2 kg/h). In 2014, Torftech Limited put a full-scale energy plant-powered demonstration plant into operation. This technology offers flexibility in product preparation for different end-use markets. This process is sensitive to changes in the size of the raw material particles [84].

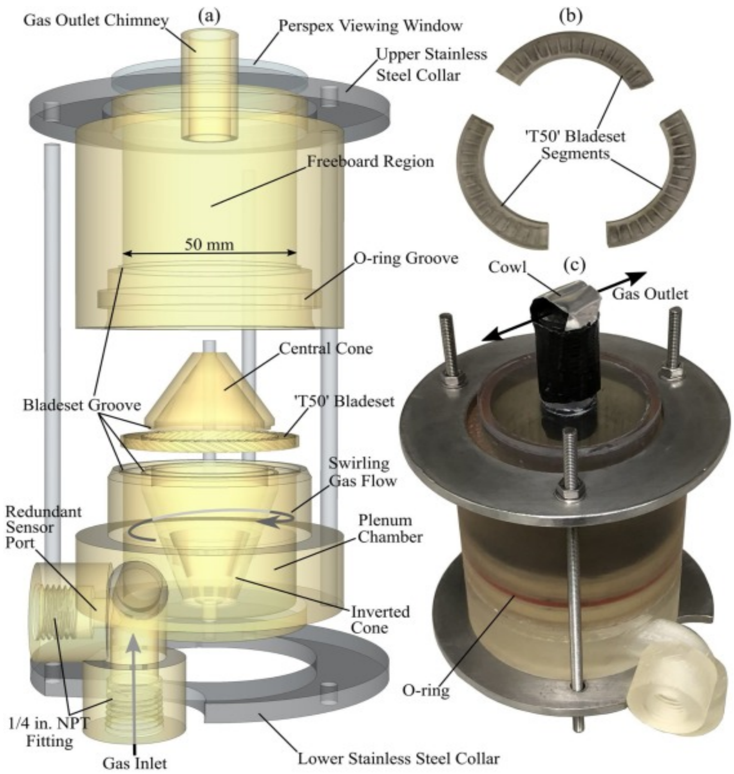

Figure 15. (**a**) Torbed small-scale CAD model dismantled; (**b**) 3D printed T50 blade segments, and (**c**) Fully-assembled 3D printed high-temperature polymer prototype. Reprinted with permission from ref. [83]. Copyright 2020 Elsevier.

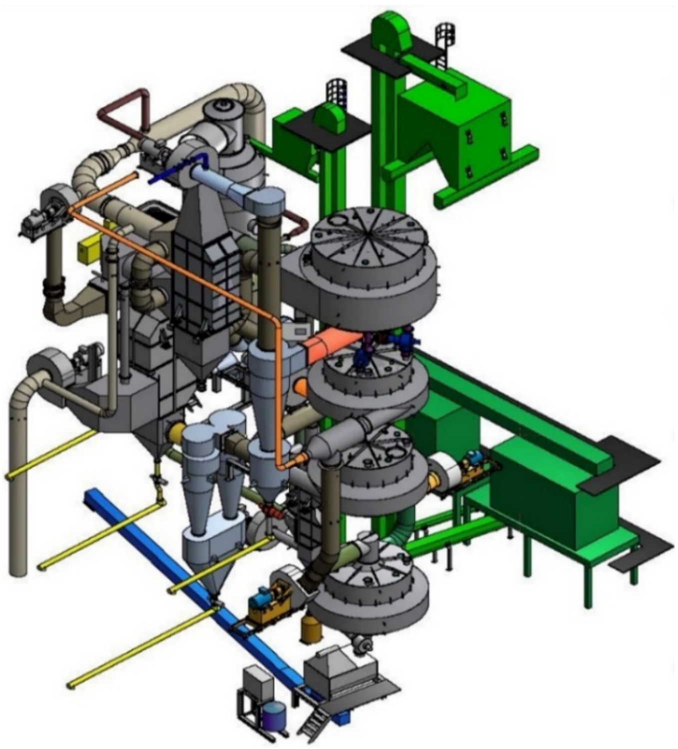

Figure 16. Torbed reactor installation by the Dutch company Blackwood Technology. Reprinted with permission from refs. [67,82]. Copyright 2013 VTT.

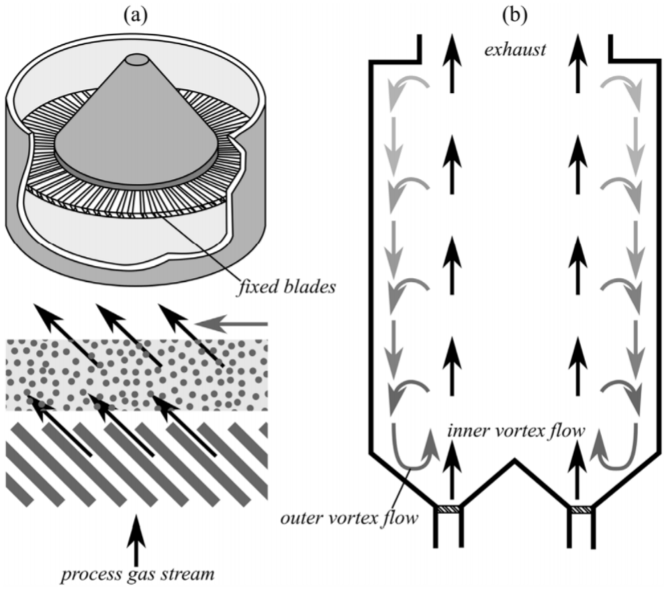

Figure 17. Circulation heat-flow-flow diagram (**b**) and 3D model (**a**). Reprinted with permission from refs. [83,85]. Copyright 2020 Elsevier.

(7) Belt reactor with pre-drying

In this case, the biomass is transported by belt in the heated reactor. A belt reactor can be configured in terms of a vibrating belt, horizontal moving bed, and oscillating belt. Biomass particles transport and heat directly through moving belts, porous belts, or vibrating belts. Multiple belts are often stacked on top of one another in a belt dryer type reactor. As biomass particles fall from one belt to the next, mixing is allowed, resulting in a more homogenous output. Vibrating belt reactors are all built in a similar manner [86]. The residence time for all particles inside the reactor can be well controlled by regulating the belt speed or the belt vibration frequency, especially in belt reactors. This method ensures that all biomass particles have the same residence time in the reactor (Figures 18 and 19). The ability to scale this reactor is limited due to strip size limitations. The maximum size of this type of reactor is 5 t/h [72]. The advantages of belt technology are the possibility of reasonable temperature control and the use of different sizes of biomass in the reactor. However, the shape of the biomass cannot be heterogeneous [65]. While a moving, porous belt transports the biomass particles, they are directly heated by a hot gaseous medium. In general, multiple strips are placed one above the other in a belt reactor. While the biomass particles fall from one belt to the other, mixing of the particles takes place, and as a result of this type of solution, a more homogeneous product is obtained. The residence time for the biomass particles in the reactor can be accurately controlled by controlling the belt speed.

Belt reactors can be considered ideal plug flow reactors, unlike certain other reactors where there is a large residence span of the biomass particles leading to either carbonized or incompletely torrefied particles that have not fully carbonized. The disadvantage of the belt reactor is the potential clogging of the open structure of the tar strip or small particles. Moreover, the capacity limits the output, making this type of reactor less appropriate for low volume density raw material. Furthermore, the possibility of regulating the temperature in the reactor is restricted because the process can only be regulated by changing the temperature of the feeding gas and the belt speed. The investment costs are cheap, but the large space requirements may limit the scalability of this type of reactor. A sketch and industrial version of the dryer are shown in Figure 20.

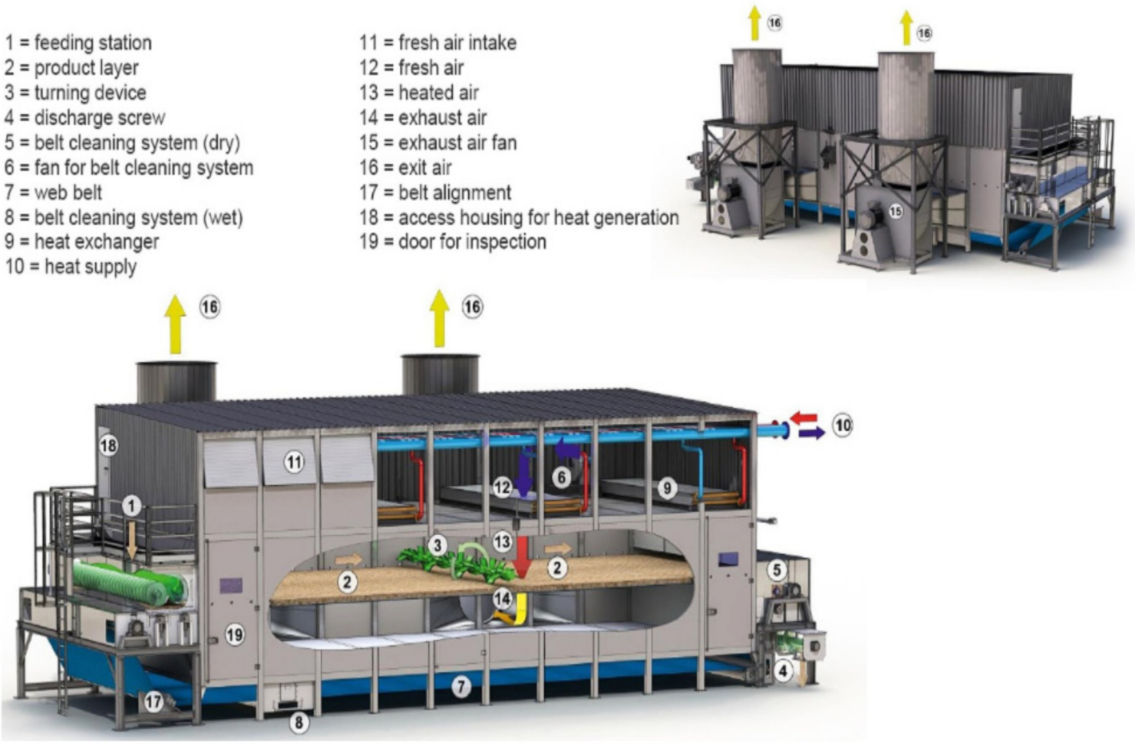

Figure 18. Belt reactors for drying and carbonization of forest biomass. Reprinted with permission from ref. [87]. Copyright 2020 Vow ASA.

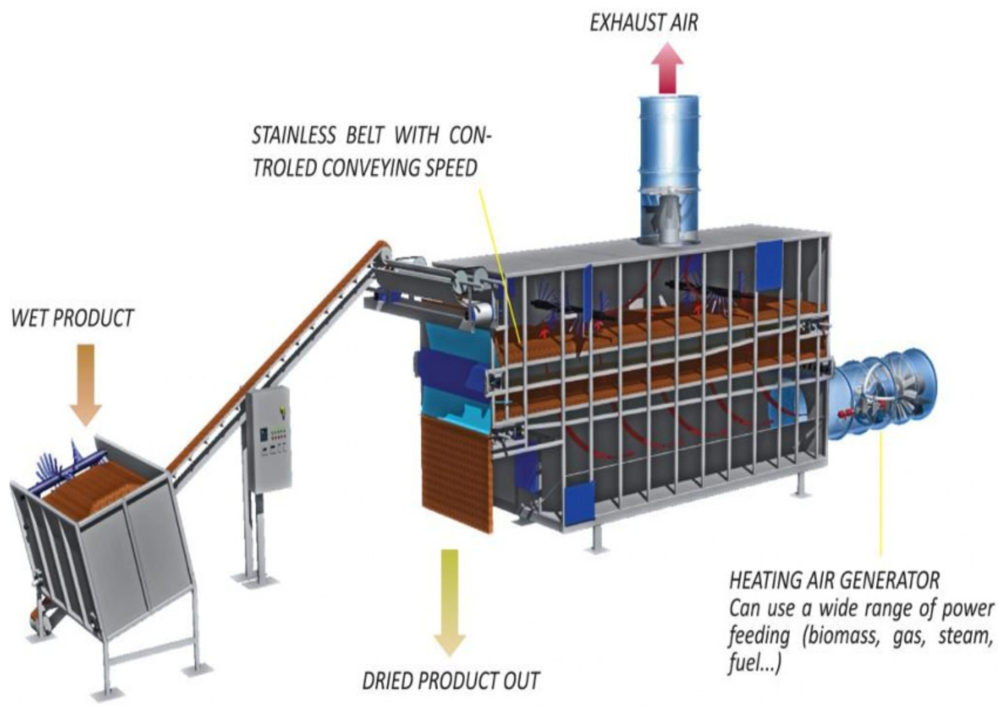

Figure 19. Installation with a belt reactor and a heat source for the biomass drying process with the possibility of adaptation to the needs of the torrefaction process. Reprinted with permission from ref. [88]. Copyright 2020 Vow ASA.

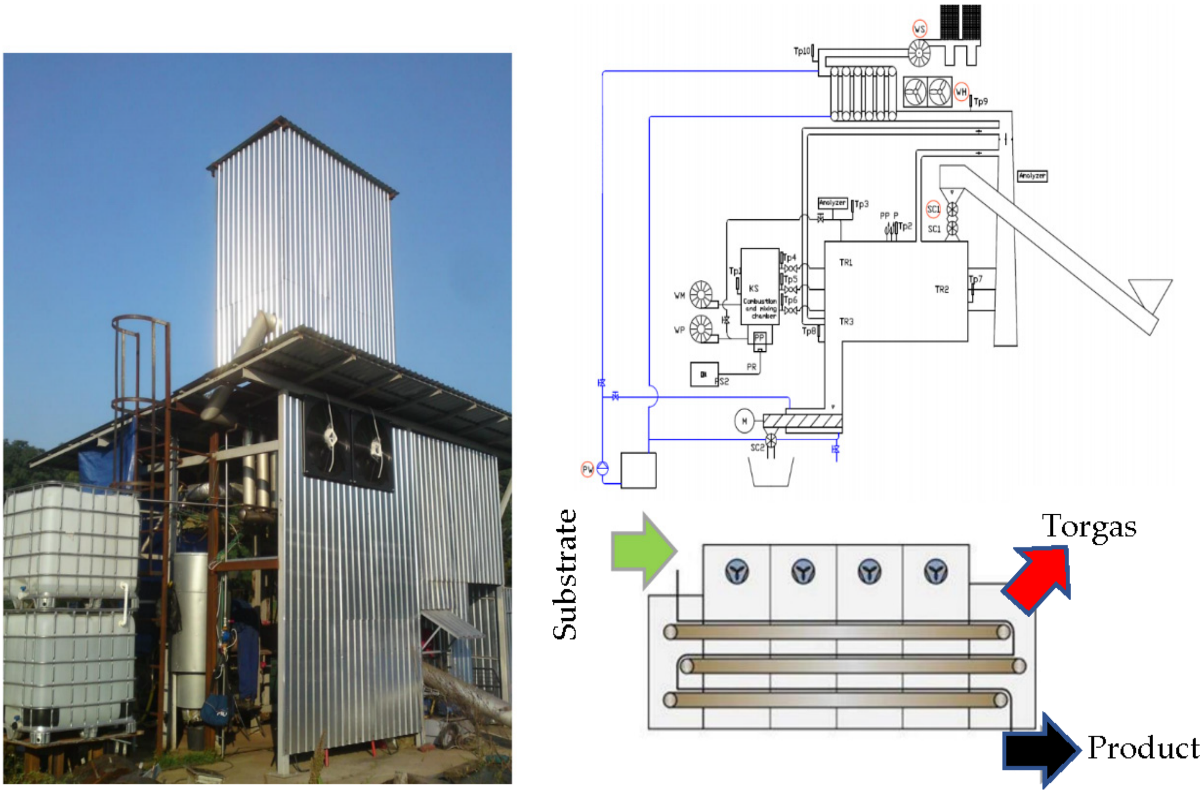

Figure 20. Multi-belt track reactor installation: Wrocław University of Technology and SBB Energy [89].

(8) Microwave reactor

The biomass is heated by microwaves in the microwave reactor (Figure 21). Microwaves have electromagnetic radiation that leads polar particles to rotate at the same frequency as microwaves, which causes friction and heating of the biomass. Generating microwaves requires a lot of electricity [90]. The reactor can process biomass with large particle sizes. In a microwave reactor, the torrefaction is usually relatively fast, and the temperature in the reactor is easy to control. However, the microwave reactor must be integrated with a traditional heater if we want to obtain homogeneously heated particles (and so a homogeneous product) [65]. The main disadvantage is that an integrated conventional heater is required, which is difficult to generate from acceptable torgas yields during the torrefaction process. This has a negative impact on energy efficiency and increases operating costs. Microwave radiation causes an electromagnetic wave from 300 MHz to 300 GHz. Microwave ovens or microwave reactors typically operate at a frequency of 2.45 GHz. Microwave irradiation causes efficient internal heating from the direct coupling of microwave energy to biomass particles. The electrical component of electromagnetic microwave radiation causes heating by two main mechanisms: dipolar polarization and ionic conductivity. Heating depends on the material's ability to heat by absorbing microwaves and converting them into heat. Previously, a facility was planned to use Scotland-based Rotawave's microwave torrefaction technology, but after the business failed, Zilkha Biomass Energy's steam-exploded Zilkha Black Pellet process will be deployed. There is not any industry-scale microwave torrefaction facility at the time.

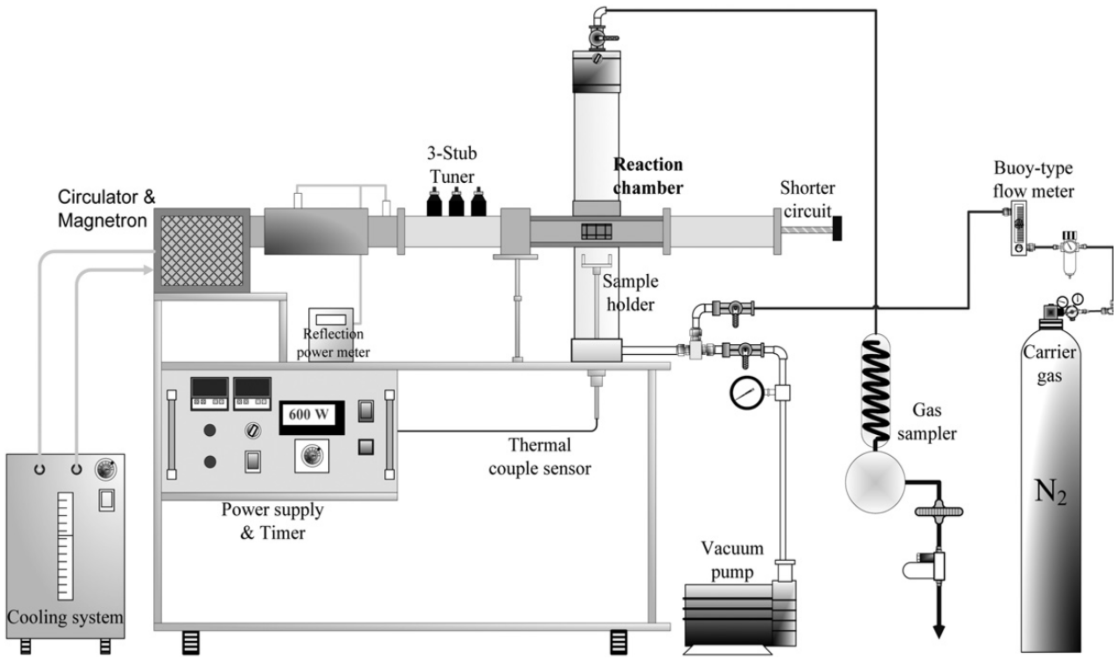

Figure 21. Reactor installation system for microwave torrefaction. Reprinted with permission from ref. [91]. Copyright 2019 Elsevier.

(9) Vibrating fluid bed reactor

In a vibrating fluid bed reactor, the bed of solids vibrates to fluidize the bed and air, or another gaseous stream is injected into the bed. A rotating vibration bowl or a linear vibration bowl is used in the reactor. The vibrating motion keeps the particles even and prevents blistering, which leads to better process efficiency. The vibrating motion also drives the particles up a helical groove in the circumferential wall of the bowl for several reasons: to facilitate removal of ash from the fuel bed, to recycle reagents or catalysts, to sequence the reactants for subsequent steps, and vibrational motion guides the particles up the sloped plate.

Vibrating fluid bed reactors use a large spring-mounted bed drive mechanism, such as a vibrating conveyor, to move the product through the reactor, as is shown in the CAD model of a vibrating bed reactor in Figure 22. The main disadvantage is that the reactor and the product are subjected to considerable overload forces. These high forces typically disintegrate the brittle product, creating unnecessary and often unwanted fine particles and waste. In addition, high overload forces will be transferred to the surrounding of the reactor, causing additional installation requirements, premature wear of the equipment, and increased noise levels [92]. Shaking fluid bed reactors solve the problem of high overload by eliminating the need for vibration and incorporating more advanced control systems that in turn eliminate the need for continuous operator involvement. The product is pushed through the reactor with a gentle, low frequency/high amplitude shaking motion that moves it forward step by step in a consistent manner called plug flow. The gravity problem is thus eliminated, allowing the least possible product deterioration, reduced foundation requirements, and minimal noise levels. A shaking fluidized bed reactor system typically has the lowest life cycle cost due to significant savings in fuel consumption and maintenance costs. The vibration level depends on the behavior and nature of the material to be dried, and the amplitude can be adjusted by altering the unbalanced weight of the vibrating devices [93].

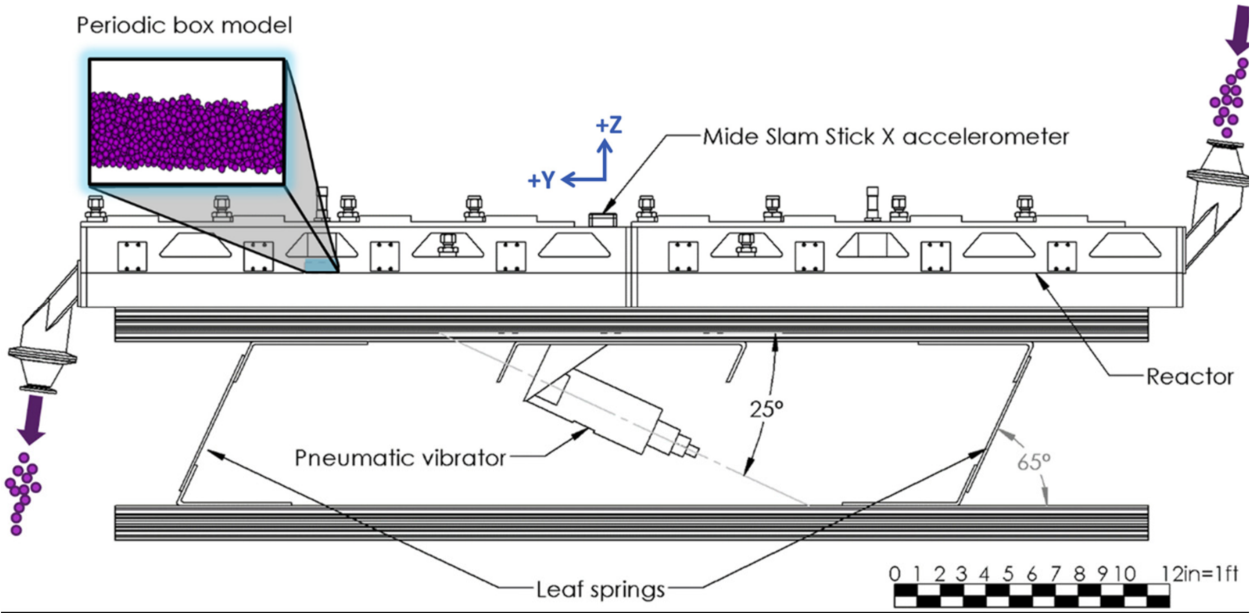

Figure 22. Computer-aided design (CAD) model of a continuous vibrating bed reactor. Reprinted with permission from ref. [92]. Copyright 2021 Elsevier.

(10) Thermosiphon-fixed bed reactor

Thermosiphons with a fixed bed reactor were introduced to improve uniform temperature distribution. Soponpongpipat et al. discovered that the average heating speed of biomass cassava rhizome was 1.40 C/min, which was 2.59 times greater than in a fixed bed reactor without thermosyphons. Compared to the other designs, this reactor produced the greatest heating value (HHV) and the lowest mass yield of 23.97 MJ/kg and 47.84%, respectively [94]. The steam generated acts as an auto catalyst in the decomposition reaction.

Figure 23 shows a thermosiphon torrefaction reactor (TSFR). It is a structural steel reactor 0.37 m wide, 0.37 m long, and 1.49 m high. It is divided into a torrefaction chamber and a heating chamber. A steel plate completely separates these two parts in the lower part of the torrefaction chamber. The torrefaction and heating chamber lengths are 0.65 m and 0.84 m, respectively. The heating chamber is divided into two zones: the thermosiphon evaporator zone (0.54 m) and the combustion zone (0.30 m), where the LPG burner is used as a heat source placed in the heating chamber. The heat is transferred from the heating chamber to the torrefying chamber through five two-phase closed thermosiphons installed inside the reactor (one in the center and four in each corner of the chamber). Each two-phase closed thermosiphon is made of a steel tube with an outer diameter of 0.06 m, a thickness of 2.5 mm, and a length of 1.10 m. The evaporator and condenser section lengths are 0.50 m and 0.60 m, respectively. The filling factor is 50% of the total evaporator volume. Volatile substances resulting from biomass torrefaction leave the reactor through two deaeration pipes installed on its side surface. Two ball valves are installed at the end of each venting tube to control the venting. These valves are closed until the biomass temperature inside the reactor reaches the boiling point of water. They are then opened to release water vapor and volatiles. After completing the torrefaction process, both ball valves are closed, and the reactor is allowed to cool to room temperature. To observe the biomass temperature distribution inside the torrefaction chamber, 10 pieces of K-type thermocouples are installed at heights of 0.94 m, 1.04 m, 1.14 m, 1.24 m, and 1.34 m [94].

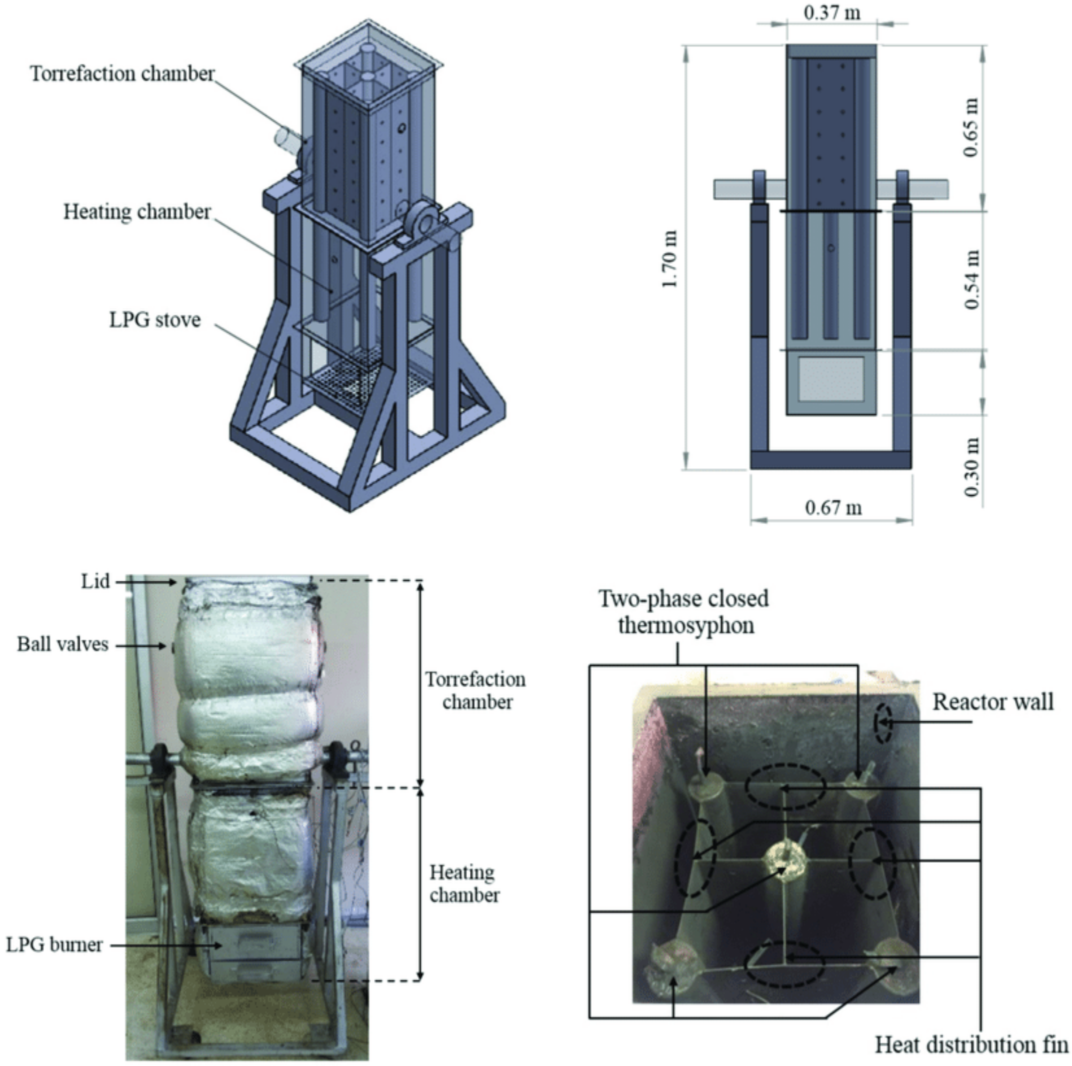

Figure 23. Thermosiphon torrefaction reactor (TSFR) [94].

(11) Counter-Flow Torrefaction Reactor

Figure 24 provides a description of an installation for the biomass torrefaction process using super-heated steam: The unit for the SHS biomass torrefaction process containing a counter-flow torrefaction reactor (Figures 24 and 25) was built at Lodz University of Technology (Faculty of Process and Environmental Engineering, Department of Safety Engineering). It includes a rolling-bed-type biomass dryer run on hot air (50 kg/h wet biomass input), a biomass dosing system for a counter-current SHS torrefaction reactor, a 200 kWth steam boiler with an economizer producing 20–180 kg/h steam capacity at 160 °C with a pressure of 2–8 bar, an electrical pre-heater 15 kW for pre-heating steam from 160–400 °C, and a condenser integrated with a scrubber. The installation includes the main heat source, which is a biomass-fired steam boiler fed with woody pellets or wood chips, integrated with an economizer used to heat up flue gas from the combustion process of air directed by a fan to a rolling-bed dryer for drying biomass, which directly improves the energy efficiency of the entire system. The material is initially shredded and goes to a dryer where it is dried from a moisture content of 40% to a moisture content of 5% (Figure 3) and goes to a counter-flow reactor where super-heated steam, subjected to a steam boiler by an electric pre-heater, torrefies the biomass in the parameters set in the central control system. The measuring system consists mainly of a Blizzard controller installed in the steam boiler control system (controlled by the excess air factor), three thermocouples on an electric steam heater and a mass flow meter, 4 thermocouples in a dryer, 6 thermocouples in a counter-current reactor, and 3 thermocouples on an electric steam heater.

Figure 24. Photos of an installation for the biomass torrefaction process using superheated steam in a counter-flow reactor and with a rolling-bed biomass dryer, in Lodz University of Technology, Lodz, Poland.

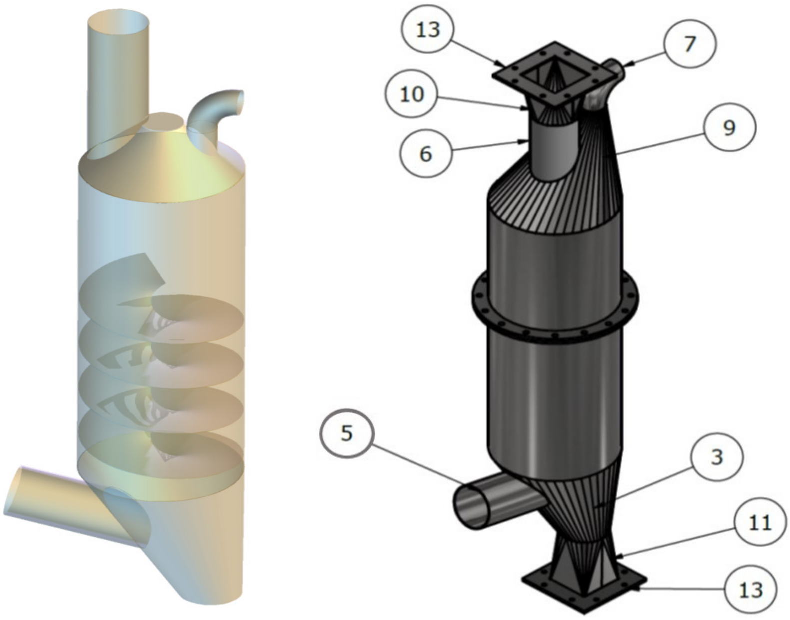

Figure 25. A 3D model made in Inventor of a counter-current reactor for biomass torrefaction with superheated steam: (**3**) insulation; (**5**) steam extraction; (**6**) biomass inlet; (**7**) torgas outlet; (**9**) snail; (**10**) sealing; (**11**) gear motor; (**13**) flange.

2.2. Level of Innovation of Individual Technologies and Industrial Perspective

Torrefaction reactors are classified into two types based on heat transmission techniques: direct and indirect heating. Heat is transmitted to the biomass in direct heating reactors by direct contact with a heated media [95]. The hot media is regulated to maintain an oxygen-free or oxygen-limited environment during torrefaction to avoid combustion. Examples of heating media are super-heated steam, exhaust gases, hot solids, and electromagnetic waves. Direct heating can be used in fixed bed, fluidized bed, rotating drum, microwave, and moving bed reactors [60,63]. In indirect heating, heat is delivered via the reactor wall to the biomass. Indirect heating makes it possible to adjust the oxygen amount easily in the reactor. Indirect heating can be applied to fixed bed, screw, and rotating drum reactors [60,63]. The reactor comparison shows that direct heating units have a higher construction cost than indirectly heated units due to the cost of the inert gas heat exchanger, microwave generator, inert gas compressor, super-heated steam generator, and particle separator (Table 5). The construction of a fluidized bed reactor is complicated, and it is extremely difficult to run. However, indirect heating reactors are easier to operate and have simpler designs. The main disadvantage of the reactor is that with a considerable thickness of the biomass bed, the heat distribution becomes unequal, and they require a large heat exchange surface to make it uniform. This results in a large space requirement and high construction costs [65,78]. As there are no moving parts or unique components in a fixed bed indirect heating reactor, it has lower construction costs.

Table 5. Comparison of biomass torrefaction reactors (own study).

Reactor Type	Medium/Heat Source	Size of Heat Transfer Surface/Reactor Surface	Difficulties in Handling the Process	Movable or Special Elements	Limitation of Scale Up
Direct Heating Reactor					
With fixed bed	Flue gas, inert gas, or super-heated steam	Not applicable	Hard	Inert gas heat exchanger or super-heated steam generator; inert gas compressor	– Non-uniform heat distribution when the thickness of the biomass bed is large – Price of inert gas – High cost of building a super-heated steam generator
With rotating drum	Exhaust or super-heated steam	Notapplicable	Hard	Drum and drive unit, super-heated steam generator	– High construction costs – Super-heated steam generator in reactor
With fluidized bed	Solid medium and/or inert gas	Not applicable	Very hard	Gas/air compressor, biomass/carrier solid separator	– Separation of biomass from solid medium – High construction costs for peripheral devices such as air/gas compressor and solids separator – Price of inert gas
With moving bed	Flue gas or Super-heated steam	Not applicable	Hard	Conveyor belt	– High construction costs of super-heated steam generator and reactor – No possibility to control the amount of oxygen in the exhaust gas
Microwave	Microwave	Not applicable	Hard	Microwave generator	– High construction costs of the reactor – High energy consumption

Table 5. *Cont.*

Reactor Type	Medium/Heat Source	Size of Heat Transfer Surface/Reactor Surface	Difficulties in Handling the Process	Movable or Special Elements	Limitation of Scale Up
Indirect Heating Reactor					
Fixed bed	Burning or electrical heater	High	Easy	No moving part	– Limited heat distribution when the thickness of the biomass in bed is large
Screw	Burning or electrical heater	High	Moderate	Screw and its drive set	– Limited heat distribution when the thickness of the biomass in bed is large
With rotating drum	Burning or electrical heater	High	Moderate	Drum and its drive set	– Limited heat distribution when the thickness of the biomass in bed is large
New reactor design (SHS)	Combustion	Small	Easy	No moving part	– Uniform heat distribution – High construction costs

Non-uniform heat distribution proves to be a limitation in scaling fixed bed reactors. This creates a low-temperature zone inside the reactor and torrefaction cannot take place. A thermosiphon (a gravity-assisted heat pipe) is chosen as the heat transfer device to solve this problem. By introducing one end of the thermosiphon into a compact mass of biomass and the other end to the heat source, heat will be transferred evenly from the hot media to the biomass without direct contact. Since the thermosiphon has very high conductivity with no moving parts, the fixed bed reactor can be easily scaled with that help. Thanks to this concept, it is possible to develop a new reactor design, which is simple in structure, needs little space, has no moving parts, is cheap, and is easy to operate.

(1) Rotary drum reactor

This is characterized by a low level of innovation compared to other reactors. Technological solutions used in the rotary drum reactor have been widely used in other devices in waste and conventional fuel utilization and incineration for many years (drum dryers and furnaces have been used since the 1950s). The low level of innovation is related to the relatively uncomplicated heat transfer technology in the rotary drum of torrefied biomass. In comparison with other processes, the method and degree of mixing the biomass with the medium that provides heat to the process are quite basic [63,65].

(2) Moving bed reactor

This reactor is characterized by an average level of innovation, as this type of moving bed is already used in many other industries including food, process engineering, pharmaceuticals, and chemical engineering, and is a fully-commercialized technology. The moving bed is not such highly advanced technology as that of fluidized bed reactors (whose operating principle is similar), and the production of this type of reactors would not be as complicated as that of Torbed reactors or fluidized bed reactors [55,65,68,96].

(3) Screw reactor

This is another reactor characterized by a low level of innovation, similar to that of the rotary drum reactor. The screw reactor deploys a similar solution to the biomass-fired boilers generally available on the market (domestic, European, and worldwide), known as screw feeders. Screw reactors use the commonly known technology of screw transferring and simultaneously mixing fuel with a medium that transfers heat to the torrefaction process [72,73].

(4) Multiple hearth furnace

The multiple hearth furnace is one of the reactors with the lowest level of innovation of any available torrefaction reactor. This type of reactor uses exactly the same solutions as charcoal furnaces and low-medium power solid fuel combustion furnaces (electric-based furnaces). Multiple hearth furnaces use solutions generally known in many other systems related to the energy industry [72,76].

(5) Fluidized bed reactor (FBR)

FBRs are one of the two reactor types, along with Torbed reactors, with the highest level of innovation among the reactors presented. This reactor uses the fluidization technique, well known for 40 years. Nevertheless, in the case of torrefaction, this technology has had to be adapted in a particular way, and it is the techniques and methods that constitute the high level of innovation [65]. Fluidized bed reactors are complicated to copy and design due to the very strictly defined parameters of the fluidization process (size and mass of the torrefied particles, speed of the fluidization process during the carbonization process, the amount of heat flux transferred to the torrefied biomass, and the geometry and shape of the reactor and chamber, in which the torrefaction process takes place. Fluidized bed reactors are based on fluidization technology used in high-power fluidized bed boilers powered by biomass, fluidized bed dryers, and many other industrial applications (such as in refrigeration, fluidized fruit freezing systems, and others) [78].

(6) Belt reactor with pre-drying

This type of reactor is a medium innovation reactor that uses a well-recognized technique. Pre-drying belt reactors are copies of the systems for drying biomass, fruit, vegetables, and biological waste. This technology has been known for about 50 years and is widely used in many industries [72,86].

(7) Torbed reactor

This type of reactor, like fluidized bed reactors, is with the highest level of innovation among all known reactors used to produce char. Torbed technology is a technique somewhat like the fluidization technology that uses cyclones at the same time. Reactors of this type have been used for over a dozen years on a pilot, demonstration, and semi-technical scale and still represent a technology under development with great potential. This technology has well-prepared intellectual property protection, which belongs to two companies, the British company Torftech Limited and the Dutch company Topell Energy (now Blackwood Technology) [80]. For several years, both companies have deployed this modern and most efficient technology for biomass carbonization. The level of innovation of Torbed technology is related to the construction of a specially designed system for heat transfer in a cyclone with a very short residence time of biomass particles and a high degree of mixing of particles and heat transfer gas [81,82]. Torbed reactors are difficult to copy and duplicate, as are fluidized bed reactors.

(8) Vibrating bed reactor

The vibrating bed reactor is characterized by a reasonably high level of innovation. It is already a well-known solution used in the energy industry, such as in boilers with vibrating grates for burning straw used by Danish companies (one example is a straw-fired boiler with a multi-stage vibrating grate by CleanTech). The vibrating bed reactor is a piece of highly advanced technology since it solves the problem of carbonization of biomass of various origins (such as forest origin biomass and that from particular purpose crops) [92].

(9) Microwave reactor

This type of reactor has an average level of innovation. Although these reactors use highly advanced microwave technology, it is a technology that has been known for many years. The innovation is that the length of electromagnetic waves is appropriately selected for the polymer structures of the biomass, which must undergo a specific level of carbonization [90,97]. These reactors have a very complex technology that is difficult to copy.

Tables 6–8 show a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis for the most common reactors in the areas of both industry and research. As can be seen, the decision as to which torrefaction reactor mostly depends on is biomass structure, moisture, size, and amount. Additionally, the residence time, reactor volume, mixing, and energy consumption are important for choosing a torrefaction reactor. Since all these factors need to be considered, there is no simple conclusion as to one proper reactor type.

Table 6. Moving bed reactor SWOT analysis.

Reactor Type	Strength	Weakness
Moving-Bed Reactor	Herbaceous and woody biomass residues (rubberwood, agriculture, orchards, and horticulture) [88,89]	The temperature distribution is not uniform, especially for indirect heating
	Can be employed with both direct and indirect heating	Lack of proper mixing
	The reactor is small and relatively basic in structure	Relatively high-pressure drop with small (<5 mm) particles
	Accurate temperature control, high heat transfer rate, uniform [90,92] product quality	Longer residence time 30–40 min
	No moving parts inside the reactor	Limited biomass size and type acceptable
	The capability of processing low-density biomass is high	
	Opportunities	Threatens
	Flexible when it comes to fueling with a specific fuel and low investment costs	When the reactor reaches scale, it can be dangerous due to the pressure and the possibility of damaging the main body of the reactor
	Possible to combine drying and torrefaction [91]	Due to the lack of proper mixing of the biomass, a risk ensues that the carrier will accumulate in the channels
	Possible to fill the reactor volume with biomass which leads to a smaller reactor and low cost	Increased risks with larger capacities
		Unproven scale-up potential non-uniform products

Table 7. Rotary drum reactor SWOT analysis.

Reactor Type	Strength	Weakness
Rotary drum Reactor	Can operate with higher biomass moisture compared to others (sawdust, stalks, switchgrass, wheat straw, and poplar) [98]	The capability of processing low-density biomass is low
	Proven technology for biomass drying, from 60% to 10%	The mixing of biomass is limited
	Uniform heat transfer due to good mixing of sliding bed	Poor control of temperature
	Can work in terms of both indirect and direct heating [63]	Lower heat transfer rates (despite good uniformity)
	Ability to use a wide range of biomass particle sizes and types	High cost and large space footprint
		Due to the friction between drum wall and biomass, the output dust increases
		Limited upscaling ability because the area of heat transfer to biomass during carbonization is limited
		Maximum capacity is reached at 10–12 t/h input or t/h torrefied product [93]
	Opportunities	Threatens
	Less gas emission, cleaner environment	Risk of use
	Relatively proven technology with other applications such as biomass drying and pyrolysis	To support the solid tumbling motion, the maximum fill volume of the reactor is limited to about 30%.

Table 8. Torbed reactor SWOT analysis.

Reactor Type	Strength	Weakness
Torbed Reactor	Good torrefaction results on woody biomass; forestry residue, rice husks, straw	Only fine wood particles, sensitive to changes in the size
	Horizontal motion on the bed causes high impact gas velocities and thus higher heat and mass transfer rates, and provides higher efficiency and lower reaction time [82]	Less control of residence time for each particle [99]
	Accepts high water content biomass feeds	Flue gas dilution by the fluidization process
	Very rapid start-up, simple to operate and automate, 90 s–5 min residence time	
	No sand bed	
	Low-pressure drop compared to the others	
	Opportunities	Threatens
	Consistent product, low carbon ashes (at combustion)	Risk of carbonization due to high temperatures
	Torbed reactor technology is considered a proven technology for various applications, including combustion	High heat transfer and high temperature make the process sensitive to variation in particle size (smaller particles could potentially lose much more volatiles compared to bigger ones)
	The installations have the lowest footprint of any similar technology. This leads to comparatively inexpensive capital investment for a given output capacity [85]	Formation of fine particles due to internal abrasion in the bed (risk of explosion in later stages)
	Available for process gas circulation, which leads to less energy consumption	
	Scalable technology (up to 25 t/h)	

The reactor techniques mentioned above have been used on a large scale. More than 50 businesses are active in the use of torrefaction technology. The properties of some of these technologies are shown in Table 9. In torrefaction technology, the USA and Netherlands emerge as leading countries. Moving bed and rotary drum reactors are the most preferable torrefaction reactors in the industry.

Table 9. Overview of some torrefaction technologies regarding facility scale and process [48,52,70,83,86,87].

Developer	Technology	Capacity (ton/y)	Country	Scale and Status
Agri-Tech Producers LLC	Belt Reactor	13,000	Columbia, South Carolina	Pilot stage, operational
APS Ekoinnowacje	Counter-flow reactor	360	Lodz, Poland	Semi-Pilot, operational
Airex	Cyclonic Bed	3000	Canada	Planning 10,000–30,000 ton/y with SUEZ partnership, available
Bio Energy Development North AB	Dedicated screw reactor	16,000	Sweden	Demonstration scale, available
New Earth Renewable Energy Fuels, Inc.	Fixed Bed	Unknown	Unknown	Out of business
Bioenergy Development & Production	Fluidized Bed	Unknown	Nova Scotia, (CAN)	Pilot, unknown
Rotawave, Ltd.	Microwave	120,000	Chester (UK)	Stopped in BC, Partnership with Maine, unknown
ECN–Andritz	Moving Bed	10,000	Stenderup (DK)	Combine technology with Andritz

Table 9. *Cont.*

Developer	Technology	Capacity (ton/y)	Country	Scale and Status
Thermya/Grupo Lantec	Moving Bed	20,000	Urnieta (SP)	Early-stage commissioning
Thermya/LMK Energy	Moving Bed	20,000	Mazingarbe (Fr)	Early-stage commissioning
Torrec	Moving Bed	10,000	Mikkeli (FI)	Demonstration scale, available
Grupo Lantec	Moving Bed	20,000	Urnieta (SP)	Demonstration scale, unknown
Integro Earth Fuels, LLC	Multiple Hearth	11,000	Greenville (USA)	Demonstration scale, unknown
Wyssmont	Multiple Hearth	Unknown	USA	Unknown
CMI NESA	Multiple Hearth	Unknown	Seraing (BE)	Unknown
Clean electricity generation	Oscillating bed	30,000	UK	Commercial scale, available
Horizon Bioenergy	Oscillating belt convenyor	45,000	Steenwijk (NL)	Dismantled after plant fire at 2012
Atmosclear SA	Rotary Drum	50,000	Latvia, New Zealand, USA	Out of business
Earth Care Products	Rotary Drum	20,000	Kansas (USA)	Demonstration scale, available
EBES AG	Rotary Drum	10,000	Frohnleiten (AU)	1 mt/h pilot plan in commissioning
Renergy/4Energy Invest	Rotary Drum	38,000	Amel (BE), Ham (Be)	Project terminated
Renergy/4Energy Invest	Rotary Drum	38,000	Ham (Be)	Project terminated
Torr-Coal B.V.	Rotary Drum	35,000	Dilsen-Stokkem (BE)	Commercial scale, available
Andritz	Rotary Drum	10,000	Frohnleiten (AT)	Demonstration scale, out of business
BioLake B.V.	Screw Convenyor	5000–1000	Eastern Europe	Pilot stage
FoxCoal B.V.	Screw Convenyor	Unknown	Winschotel (NL)	Pilot, now bankrupt
Solvay / New Biomass Energy	Screw Reactor	80,000	(FR), Missisippi (USA)	Commercial scale, available
Arigma Fuels	Screw Reactor	20,000	Ireland	Commercial scale, available
Topell Energy	Torbed, Fluidized bed	60,000	Duiven (NL)	Commercial scale, available
Airless Systems	Unknown	40,000	Latvia	Out of business
HM3 Energy	Unknown	Unknown	Oregan, US	Pilot Demo plant
River Basin energy	Unknown	Unknown	Laramie, Wyoming (USA)	Pilot stage
Torrefaction Systems Inc.	Unknown	Unknown	Unknown	Pilot
WPAC	Unknown	35,000	Unknown	Unknown

3. Conclusions and Recommendations

The current work is presented in two stages, providing a comprehensive picture of the thermochemical decomposition technologies of biomass. Here in Part 1 of the research, the purpose, scope, and conditions of the technologies are discussed. In addition, the methods, techniques, and research tools, including initial preparation methods of biomass for the torrefaction process, are presented. An overview of reactors for torrefaction processes and technologies for the production of super-heated steam for technological purposes of torrefaction as well as the optimal use of heat in the torrefaction process are also presented.

The majority of the changes identified are linked to material flow through the reactor, material heating method, process heat source, and torgas treatment. The reactor choice is highly reliant on the feedstock, the use of the products, and the cost considerations. Although there is no obvious choice of torrefaction reactor, rotary drum and moving bed technologies may suggest themselves with their better temperature control and common usage as torrefaction reactors. The study also presents the process assumptions for the steam generator, biomass dryer, and the thermochemical biomass conversion reactor for the optimization of the residence time of the raw material, as well as the process assumptions allowing determination of the physicochemical properties and their assessment for biomass from various raw materials. According to the authors, the optimal solution would include using an electric steam generator and overheating in a gas steam superheater in the torrefaction process.

The latest biomass dryer and biomass torrefaction reactor technical solutions exhibit similar functionalities in terms of both dryer and reactor. During consultations with the industry and research institutes, a consensus was found that the most optimal solution in terms of technology, continuity of operation, and economic terms for the future manufacture of biomass torrefaction installations would include a combination of the dryer and the reactor into one device, hereinafter referred to as the Dryer-Reactor. This technology will reduce production costs and improve the efficiency of the entire process while enabling continuous operation. This type of device will be tested in the following stages of our work.

Future work: In Part 2, biomass pyrolizer technologies will be examined on a commercial and pilot scale and compared with torrefaction technologies with economical and environmentally friendly characteristics.

Author Contributions: S.S. and P.P., methodology; P.P., W.L., H.U., data collection; P.P., R.Ś., W.L. and H.U., investigation; R.Ś. and R.M., resources; P.P., H.U. and W.L., data curation; S.S., P.P., H.U., W.L. and S.L., writing—original draft preparation; P.P, H.U., W.L. and S.S., writing—review and editing; P.P., H.U. and W.L., visualization; S.S. and S.L., supervision; S.S. and S.L., project administration, funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: The studies presented were financed by the National Center of Research and Development (NCBR) Poland under the research program LIDER. The research and development project is entitled by the acronym BIOCARBON, with the title "Modern technology biomass torrefaction process to produce fuel mixtures, biocoal as additives for fertilizers, activated carbon for energy sector, agriculture, civil engineering and chemical industry", "LIDER IX" NCBR 2014-2020 (grant no. LIDER/43/0155/L-9/17/NCBR/2018). The research was also supported by the National Centre of Science from Krakow Research (grant no. 2011/03/N/ST8/02776).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

References

1. Szramowiat-Sala, K.; Korzeniewska, A.; Sornek, K.; Marczak, M.; Wierońska, F.; Berent, K.; Gołaś, J.; Filipowicz, M. The properties of particulate matter generated during wood combustion in in-use stoves. *Fuel* **2019**, *253*, 792–801. [CrossRef]
2. Marczak, M.; Wierońska, F.; Burmistrz, P.; Strugała, A.; Kogut, K.; Lech, S. Investigation of subbituminous coal and lignite combustion processes in terms of mercury and arsenic removal. *Fuel* **2019**, *251*, 572–579. [CrossRef]

3. Zhang, Y.; Cui, Y.; Chen, P.; Liu, S.; Zhou, N.; Ding, K.; Fan, L.; Peng, P.; Min, M.; Cheng, Y.; et al. Gasification Technologies and Their Energy Potentials. In *Sustainable Resource Recovery and Zero Waste Approaches*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 193–206. [CrossRef]
4. Ünyay, H.; Yılmaz, F.; Başar, İ.A.; Altınay Perendeci, N.; Çoban, I.; Şahinkaya, E. Effects of organic loading rate on methane production from switchgrass in batch and semi-continuous stirred tank reactor system. *Biomass Bioenergy* **2022**, *156*, 106306. [CrossRef]
5. Szufa, S.; Wielgosiński, G.; Piersa, P.; Czerwińska, J.; Dzikuć, M.; Adrian, Ł.; Lewandowska, W.; Marczak, M. Torrefaction of Straw from Oats and Maize for Use as a Fuel and Additive to Organic Fertilizers—TGA Analysis, Kinetics as Products for Agricultural Purposes. *Energies* **2020**, *13*, 2064. [CrossRef]
6. Parthasarathy, P.; Narayanan, K.S. Hydrogen production from steam gasification of biomass: Influence of process parameters on hydrogen yield—A review. *Renew. Energy* **2014**, *66*, 570–579. [CrossRef]
7. Kondo, H.; Owen, L.A. 5.12 Paleoseismology. In *Treatise on Geomorphology*; Elsevier: Amsterdam, The Netherlands, 2013; pp. 267–299. [CrossRef]
8. Ghosh, P.; Sengupta, S.; Singh, L.; Sahay, A. Life cycle assessment of waste-to-bioenergy processes: A review. *Bioreactors* **2020**, *8*, 105–122. [CrossRef]
9. Adrian, Ł.; Piersa, P.; Szufa, S.; Cebula, A.; Kowalczyk, S. Experimental Research and Thermographic Analysis of Heat Transfer Processes in a Heat Pipe Heat Exchanger Utilizing as a Working Fluid R134A. In *Renewable Energy Sources: Engineering, Technology, Innovation*; Springer: Cham, Switzerland, 2018; pp. 413–421. [CrossRef]
10. Isahak, W.N.R.W.; Hisham, M.W.M.; Yarmo, M.A.; Yun Hin, T.Y. A review on bio-oil production from biomass by using pyrolysis method. *Renew. Sustain. Energy Rev.* **2012**, *16*, 5910–5923. [CrossRef]
11. Szufa, S.; Piersa, P.; Adrian, Ł.; Sielski, J.; Grzesik, M.; Romanowska-Duda, Z.; Piotrowski, K.; Lewandowska, W. Acquisition of Torrefied Biomass from Jerusalem Artichoke Grown in a Closed Circular System Using Biogas Plant Waste. *Molecules* **2020**, *25*, 3862. [CrossRef]
12. Chen, W.-H.; Lin, B.-J.; Lin, Y.-Y.; Chu, Y.-S.; Ubando, A.T.; Show, P.L.; Ong, H.C.; Chang, J.-S.; Ho, S.-H.; Culaba, A.B.; et al. Progress in biomass torrefaction: Principles, applications and challenges. *Prog. Energy Combust. Sci.* **2021**, *82*, 100887. [CrossRef]
13. Jenkins, R.W.; Sutton, A.D.; Robichaud, D.J. Pyrolysis of Biomass for Aviation Fuel. In *Biofuels forAviation*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 191–215. [CrossRef]
14. Nunes, L.J.R.; De Oliveira Matias, J.C.; Da Silva Catalão, J.P. *Torrefaction of Biomass for Energy Applications*; Elsevier: Amsterdam, The Netherlands, 2017. [CrossRef]
15. Hohn, E. *Article on the Theory of Drying and Torrefaction*; Springer: Berlin/Heidelberg, Germany, 1919; Volume 63, pp. 821–826.
16. Emrich, W. *Handbook of Charcoal Making. Solar Energy R&D in the European Community*; Series E, Energy from Biomass; Springer: Dordrecht, The Netherlands, 1985; Volume 7.
17. Bourgeois, J.P.; Doat, J. Torrefied wood from temperate and tropical species. Advantages and prospects. In *Proceedings of the Bioenergy 84, Volume III. Biomass Conversion, Goteborg, Sweden, 15–21 June 1984*; Elsevier Applied Science Publishers: Amsterdam, The Netherlands, 1984.
18. Arjona, J.; Rios, G.; Gibert, H.; Vincent, J. Gas-Fluidized Bed Torrefaction of Coffee. *Cafe Cacao* **1979**, *23*, 119–228.
19. Miele, A.E. Method and System for the Torrefaction of Lignocellulosic Material. Available online: https://patents.google.com/patent/EP2758501A2/en (accessed on 5 February 2022).
20. Felfli, F.; Luengo, C.; Beaton, P.; Suarez, J. Efficiency test for bench unit torrefaction and characterization of torrefied biomass. In Proceedings of the Fourth Biomass Conference of the Americas, Oakland, CA, USA, 29 August–2 September 1999; pp. 589–592.
21. Felfli, F.; Luengo, C.; Bezzon, G.; Soler, P.; Mora, W. A Numerical Model for Biomass Torrefaction. In Proceedings of the 10th European Conference and Technology Exhibition Biomass for Energy and Industry, Wurzburg, Germany, 8–11 June 1998; pp. 1596–1599.
22. Felfli, F.; Luengo, C.; Bezzon, G.; Soler, P. Bench unit for biomass residues torrefaction. In Proceedings of the 10th European Conference and Technology Exhibition Biomass for Energy and Industry, Wurzburg, Germany, 8–11 June 1998; pp. 1593–1595.
23. Lehrfeld, J. Cation Exchange Resins Prepared by Torrefaction of Phytic Acid with Some Agricultural Residues. *Abstr. Pap. Am. Chem. Soc.* **1997**, *23*, 47.
24. Pentananunt, R.; Rahman, A.N.M.M.; Bhattacharya, S.C. Upgrading of biomass by means of torrefaction. *Energy* **1990**, *15*, 1175–1179. [CrossRef]
25. Szufa, S.; Adrian, Ł.; Piersa, P.; Romanowska-Duda, Z.; Grzesik, M.; Cebula, A.; Kowalczyk, S. Experimental studies on energy crops torrefaction process using batch reactor to estimate torrefaction temperature and residence time. In *Renewable Energy Sources: Engineering, Technology, Innovation*; Mudryk, K., Werle, S., Eds.; Springer: Berlin/Heidelberg, Germany, 2018; pp. 365–373. [CrossRef]
26. Szufa, S.; Piersa, P.; Adrian, Ł; Czerwińska, J.; Lewandowski, A.; Lewandowska, W.; Sielski, J.; Dzikuć, M.; Wróbel, M.; Jewiarz, M.; et al. Sustainable Drying and Torrefaction Processes of Miscanthus for Use as a Pelletized Solid Biofuel and Biocarbon-Carrier for Fertilizers. *Molecules* **2021**, *26*, 1014. [CrossRef]
27. Dutta, A.; Leon, M.A. *Pros and Cons of Torrefaction of Woody Biomass*; University of Guelph: Guelph, ON, Canada, 2006; pp. 1–19.

28. Başar, I.A.; Çoban, Ö.; Göksungur, M.Y.; Eskicioğlu, Ç; Perendeci, N.A. Enhancement of lignocellulosic biomass anaerobic digestion by optimized mild alkaline hydrogen peroxide pretreatment for biorefinery applications. *J. Environ. Manag.* **2021**, *298*, 113539. [CrossRef]
29. Başar, I.; Ünşar, E.K.; Ünyay, H.; Perendeci, N. Ethanol, methane, or both? Enzyme dose impact on ethanol and methane production from untreated energy crop switchgrass varieties. *Renew. Energy* **2019**, *149*, 287–297. [CrossRef]
30. Başar, I.A.; Perendeci, N.A. Optimization of zero-waste hydrogen peroxide—Acetic acid pretreatment for sequential ethanol and methane production. *Energy* **2021**, *225*, 120324. [CrossRef]
31. Duranay, N.D.; Akkuş, G. Solid fuel production with torrefaction from vineyard pruning waste. *Biomass Convers. Biorefinery* **2021**, *11*, 2335–2346. [CrossRef]
32. Ramos-Carmona, S.; Pérez, J.F.; Pelaez-Samaniego, M.R.; Barrera, R.; Garcia-Perez, M. Effect of torrefaction temperature on properties of Patula pine. *Maderas Cienc. y Tecnol.* **2017**, *19*, 39–50. [CrossRef]
33. Kymäläinen, M.; Havimo, M.; Keriö, S.; Kemell, M.; Solio, J. Biological degradation of torrefied wood and charcoal. *Biomass Bioenergy* **2014**, *71*, 170–177. [CrossRef]
34. Chen, W.-H.; Lin, B.-J.; Colin, B.; Pétrissans, A.; Pétrissans, M. A study of hygroscopic property of biomass pretreated by torrefaction. *Energy Procedia* **2019**, *158*, 32–36. [CrossRef]
35. Sá, L.C.R.; Loureiro, L.M.E.F.; Nunes, L.J.R.; Mendes, A.M. Torrefaction as a Pretreatment Technology for Chlorine Elimination from Biomass: A Case Study Using Eucalyptus globulus Labill. *Resources* **2020**, *9*, 54. [CrossRef]
36. Piersa, P.; Szufa, S.; Czerwińska, J.; Unyay, H.; Adrian, Ł.; Wielgosinski, G.; Obraniak, A.; Lewandowska, W.; Marczak-Grzesik, M.; Dzikuć, M.; et al. Pine Wood and Sewage Sludge Torrefaction Process for Production Renewable Solid Biofuels and Biochar as Carbon Carrier for Fertilizers. *Energies* **2021**, *14*, 8176. [CrossRef]
37. Shafizadeh, F.; McGinnis, G. Chemical composition and thermal analysis of cottonwood. *Carbohydr. Res.* **1971**, *16*, 273–277. [CrossRef]
38. Cao, X.; Ro, K.S.; Libra, J.A.; Kammann, C.I.; Lima, I.; Berge, N.; Li, L.; Li, Y.; Chen, N.; Yang, J.; et al. Effects of Biomass Types and Carbonization Conditions on the Chemical Characteristics of Hydrochars. *J. Agric. Food Chem.* **2013**, *61*, 9401–9411. [CrossRef] [PubMed]
39. Grycova, B.; Pryszcz, A.; Krzack, S.; Klinger, M.; Lestinsky, P. Torrefaction of biomass pellets using the thermogravimetric analyser. *Biomass Convers. Biorefinery* **2020**, *11*, 2837–2842. [CrossRef]
40. Granados, D.A.; Basu, P.; Chejne, F.; Nhuchhen, D.R. Detailed Investigation into Torrefaction of Wood in a Two-Stage Inclined Rotary Torrefier. *Energy Fuels* **2016**, *31*, 647–658. [CrossRef]
41. Poudel, J.; Karki, S.; Oh, S. Valorization of Waste Wood as a Solid Fuel by Torrefaction. *Energies* **2018**, *11*, 1641. [CrossRef]
42. Acharya, B.; Dutta, A.; Minaret, J. Review on comparative study of dry and wet torrefaction. *Sustain. Energy Technol. Assess.* **2015**, *12*, 26–37. [CrossRef]
43. Romanowska-Duda, Z.; Szufa, S.; Grzesik, M.; Piotrowski, K.; Janas, R. The Promotive Effect of *Cyanobacteria* and *Chlorella* sp. Foliar Biofertilization on Growth and Metabolic Activities of Willow (*Salix viminalis* L.) Plants as Feedstock Production, Solid Biofuel and Biochar as C Carrier for Fertilizers via Torrefaction Process. *Energies* **2021**, *14*, 5262. [CrossRef]
44. Yang, W.; Wu, S.; Wang, H.; Ma, P.; Shimanouchi, T.; Kimura, Y.; Zhou, J. Effect of wet and dry torrefaction process on fuel properties of solid fuels derived from bamboo and Japanese cedar. *BioResources* **2017**, *12*, 8629–8640. [CrossRef]
45. Szufa, S. Zastosowanie przegrzanej pary w procesie toryfikacji biomasy. *Przemysł Chem.* **2020**, *1*, 123–127. [CrossRef]
46. Ibbett, R.; Gaddipati, S.; Davies, S.; Hill, S.; Tucker, G. The mechanisms of hydrothermal deconstruction of lignocellulose: New insights from thermal–analytical and complementary studies. *Bioresour. Technol.* **2011**, *102*, 9272–9278. [CrossRef] [PubMed]
47. Garrote, G.; Domínguez, H.; Parajó, J.C. Hydrothermal processing of lignocellulosic materials. *Holz Als Roh-Und Werkst.* **1999**, *57*, 191–202. [CrossRef]
48. Wielgosiński, G.; Czerwińska, J.; Szufa, S. Municipal Solid Waste Mass Balance as a Tool for Calculation of the Possibility of Implementing the Circular Economy Concept. *Energies* **2021**, *14*, 1811. [CrossRef]
49. Libra, J.A.; Ro, K.S.; Kammann, C.; Funke, A.; Berge, N.D.; Neubauer, Y.; Titirici, M.-M.; Fühner, C.; Bens, O.; Kern, J.; et al. Hydrothermal carbonization of biomass residuals: A comparative review of the chemistry, processes and applications of wet and dry pyrolysis. *Biofuels* **2011**, *2*, 71–106. [CrossRef]
50. Kambo, H.S.; Dutta, A. A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. *Renew. Sustain. Energy Rev.* **2015**, *45*, 359–378. [CrossRef]
51. Funke, A.; Reebs, F.; Kruse, A. Experimental comparison of hydrothermal and vapothermal carbonization. *Fuel Process. Technol.* **2013**, *115*, 261–269. [CrossRef]
52. Tumuluru, J.S.; Wright, C.T.; Hess, J.R.; Kenney, K.L. A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application. *Biofuels Bioprod. Biorefin.* **2011**, *5*, 683–707. [CrossRef]
53. Reza, M.T.; Lynam, J.; Uddin, M.H.; Coronella, C.J. Hydrothermal carbonization: Fate of inorganics. *Biomass Bioenergy* **2013**, *49*, 86–94. [CrossRef]
54. Yan, W.; Acharjee, T.C.; Coronella, C.J.; Vásquez, V.R. Thermal pretreatment of lignocellulosic biomass. *Environ. Prog. Sustain. Energy* **2009**, *28*, 435–440. [CrossRef]

55. Tumuluru, J.S.; Sokhansanj, S.; Wright, C.T.; Richard, D. *Boardman. Biomass Torrefaction Process Review and Moving Bed Torrefaction System Model Development*; U.S. Department of Energy Office of Scientific and Technical Information: Idaho Falls, ID, USA, 2010. [CrossRef]
56. Hoekman, S.K.; Broch, A.; Robbins, C. Hydrothermal Carbonization (HTC) of Lignocellulosic Biomass. *Energy Fuels* **2011**, *25*, 1802–1810. [CrossRef]
57. Mustaza, M.N.F.; Mizan, M.N.; Yoshida, H.; Izhar, S. Torréfaction of Mangrove Wood by Introducing Superheated Steam for Biochar Production. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *765*, 012027. [CrossRef]
58. Zhang, D.; Chen, X.; Qi, Z.; Wang, H.; Yang, R.; Lin, W.; Li, J.; Zhou, W.; Ronsse, F. Superheated steam as carrier gas and the sole heat source to enhance biomass torrefaction. *Bioresour. Technol.* **2021**, *331*, 124955. [CrossRef]
59. Adrian, Ł.; Szufa, S.; Piersa, P.; Mikołajczyk, F. Numerical Model of Heat Pipes as an Optimization Method of Heat Exchangers. *Energies* **2021**, *14*, 7647. [CrossRef]
60. Organic Waste Torrefaction—A Review: Reactor Systems, and the Biochar Properties. Available online: https://www.intechopen.com/chapters/54381 (accessed on 5 February 2022).
61. Stępień, P. Mathematical modeling of torrefaction of refuse-derived alternative fuel Modelowanie matematyczne toryfikacji paliwa pochodzącego z odpadów. *Chem. Ind.* **2017**, *96*, 227–231. [CrossRef]
62. Stępień, P.; Mysior, M.; Białowiec, A. *Problemy Techniczne i Technologiczne oraz Potencjał Aplikacyjny Toryfikacji Odpadów*; Wrocław Wydaw Uniw Wrocławskiego: Wrocław, Poland, 2018; pp. 59–78.
63. Eriksson, A.M. Torrefaction and gasification of biomass. The Potential of Torrefaction Combined with Entrained Flow Gasification. Ph.D. Thesis, KTH Royal Institute of Technology Stockholm, Stockholm, Sweden, 2012.
64. Cahyanti, M.N.; Doddapaneni, T.R.K.C.; Kikas, T. Biomass torrefaction: An overview on process parameters, economic and environmental aspects and recent advancements. *Bioresour. Technol.* **2020**, *301*, 122737. [CrossRef]
65. Alok, D. Torrefaction of Biomass. Master's Thesis, Dalhousie University, Halifax, NS, Canada, 2011.
66. Eyre, A. Torrefaction Demonstration Plants. Master's Thesis, Dalhousie University, Halifax, NS, Canada, 2012; p. 27.
67. Wilèn, C.; Jukola, P.; Järvinen, T.; Sipilä, K.; Verhoeff, F.; Kiel, J. *Wood Torrefaction—Pilot Tests and Utilisation*; VTT: Espoo, Finland, 2013; Volume 122.
68. Verhoeff FAdell i Arnuelos, A.; Boersma, A.R.; Pels, J.R.; Lensselink, J.; Kiel, J.H.A.; Schukken, H. Torrefaction Technology for the Production of Solid Bioenergy Carriers from Biomass and Waste. 2011. Available online: https://www.torrcoal.com/cms/wp-content/uploads/Torrefaction-Technology-for-solid-bioenergy-carriers-from-biomass-and-waste.pdf (accessed on 5 February 2022).
69. Koppejan, J.; Sokhansanj, S.; Melin, S.; Madrali, S. Status overview of torrefaction technologies (IEA Bioenergy Task 32). *IEA Bioenergy Task* **2012**, *32*, 1–54.
70. Negi, S.; Jaswal, G.; Dass, K.; Mazumder, K.; Elumalai, S.; Roy, J.K. Torrefaction: A sustainable method for transforming of agri-wastes to high energy density solids (biocoal). *Rev. Environ. Sci. Biotechnol.* **2020**, *19*, 463–488. [CrossRef]
71. Shirzad, M.; Karimi, M.; Silva, J.A.C.; Rodrigues, A.E. Moving Bed Reactors: Challenges and Progress of Experimental and Theoretical Studies in a Century of Research. *Ind. Eng. Chem. Res.* **2019**, *58*, 9179–9198. [CrossRef]
72. Ronsse, F.; Nachenius, R.W.; Prins, W. Carbonization of Biomass. In *Recent Advances in Thermo-Chemical Conversion of Biomass*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 293–324. [CrossRef]
73. Bergman, P.C.A.; Boersma, A.R.; Zwart, R.W.R.; Kiel, J.H.A. *Torrefaction for Biomass Co-Firing in Existing Coal-Fired Power Stations*; Report No. ECN-C-05-013; Energy Centre of Netherlands: Petten, The Netherlands, 2005.
74. Wild, M.; Calderón, C. Torrefied Biomass and Where Is the Sector Currently Standing in Terms of Research, Technology Development, and Implementation. *Front. Energy Res.* **2021**, *9*, 1–6. [CrossRef]
75. Eseyin, A.E.; Steele, P.H.; Pittman, C.U. Current trends in the production and applications of torrefied wood/biomass—A review. *BioResources* **2015**, *10*, 8812–8858. [CrossRef]
76. Stelmach, J.; Kuncewicz, C.; Szufa, S.; Jirout, T.; Rieger, F. The Influence of Hydrodynamic Changes in a System with a Pitched Blade Turbine on Mixing Power. *Processes* **2020**, *9*, 68. [CrossRef]
77. Demey, H.; Rodriguez-Alonso, E.; Lacombe, E.; Grateau, M.; Jaricot, N.; Chatroux, A.; Thiery, S.; Marchand, M.; Melkior, T. Upscaling Severe Torrefaction of Agricultural Residues to Produce Sustainable Reducing Agents for Non-Ferrous Metallurgy. *Metals* **2021**, *11*, 1905. [CrossRef]
78. Intensified by Design© for the intensification of processes involving solids handling. Available online: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5be85808f&appId=PPGMS (accessed on 5 February 2022).
79. Energy, A. Industrial Applications Of Solid Biofuels—Carbonfx Technology-Airex Energy. CCRA. 2012. Available online: http://www.cancarb.ca/pdfs/pubs/Airex%20CCRA%20-%20Torrefaction%20Bertrand.pdf (accessed on 5 February 2022).
80. Torrefaction and Pelleting. Available online: https://pellets-wood.com/torrefaction-and-pelleting-o93.html (accessed on 5 February 2022).
81. Adrian, Ł.; Szufa, S.; Piersa, P.; Kuryło, P.; Mikołajczyk, F.; Kurowski, K.; Pochwała, S.; Obraniak, A.; Stelmach, J.; Wielgosiński, G.; et al. Analysis and Evaluation of Heat Pipe Efficiency to Reduce Low Emission with the Use of Working Agents R134A, R404A and R407C, R410A. *Energies* **2021**, *14*, 1926. [CrossRef]
82. Topell Energy. From Torbed Reactor System 2009. Available online: www.topellenergy.com/technology/torbed-reactor-system/ (accessed on 8 January 2022).

83. McDonough, J.R.; Law, R.; Reay, D.A.; Groszek, D.; Zivkovic, V. Miniaturisation of the toroidal fluidisation concept using 3D printing. *Chem. Eng. Res. Des.* **2020**, *160*, 129–140. [CrossRef]
84. Koppejan, J.; Sokhansanj, S.; Melin, S.; Madrali, S. Status Overview of Torrefaction Technologies, A Review of the Commercialization Status of Biomass Torrefaction. 2012. Available online: https://www.ieabioenergy.com/wp-content/uploads/2015/11/IEA_Bioenergy_T32_Torrefaction_update_2015b.pdf (accessed on 5 February 2022).
85. Blissett, R.; Sommerville, R.; Rowson, N.; Jones, J.; Laughlin, B. Valorisation of rice husks using a TORBED® combustion process. *Fuel Process. Technol.* **2017**, *159*, 247–255. [CrossRef]
86. Schmidt, L. *A Comprehensive Analysis of Torrefaction Technologies for Producing Advanced Wood Pellets*; Report Produced for the Council of Western State Foresters; FutureMetrics: Bethel, ME, USA, 2021.
87. BTL Dryers. Available online: https://www.pawlica.eu/products/industrial-dryers/belt-dryers/bioplant-residues/btl.html (accessed on 8 January 2022).
88. Beltomatic Continuous Belt Dryer. Available online: http://www.biogreen-energy.com/beltomatic-belt-dryer (accessed on 1 February 2022).
89. Martin, D.; Halina, P.; Michal, C.; Brzdekiewicz Artur, S.Z. Technologies for the Production of Biochar—Advantages and Disadvantages. *ICIMB Inst. Ceram. i Mater. Bud. Build. Mater.* **2015**, *21*, 7–21.
90. Microwave Torrefaction of Biomass. 2011. Available online: https://patentimages.storage.googleapis.com/c0/12/08/a0248e1f2bbdcc/US20110219679A1.pdf (accessed on 5 February 2022).
91. Osman, M.S.; Kong, S.; Law, M.C. *Numerical Simulation and Experimental Validation of Microwave Torrefaction for Empty Fruit Bunches Pellet*; E-Bangi: Bangi, Malaysia, 2019; p. 16.
92. Hartig, J.; Howard, H.C.; Stelmach, T.J.; Weimer, A.W. DEM modeling of fine powder convection in a continuous vibrating bed reactor. *Powder Technol.* **2021**, *386*, 209–220. [CrossRef]
93. Soponpongpipat, N.; Nanetoe, S.; Comsawang, P. Thermal degradation of cassava rhizome in thermosyphon-fixed bed torrefaction reactor. *Processes* **2020**, *8*, 267. [CrossRef]
94. Shaking Fluid Bed Dryer versus Vibrating Fluid Bed Dryer. Available online: https://temaprocess.com/vibrating-fluid-bed-dryer/ (accessed on 12 January 2022).
95. Dhungana, A.; Basu, P.; Dutta, A. Effects of Reactor Design on the Torrefaction of Biomass. *J. Energy Resour. Technol.* **2012**, *134*, 041801. [CrossRef]
96. Crnogaca, B. Torrefaction as a process for biomass conversion into biocoal. *Tehnika* **2017**, *72*, 323–327. [CrossRef]
97. Wang, M.J.; Huang, Y.F.; Chiueh, P.T.; Kuan, W.H.; Lo, S.L. Microwave-induced torrefaction of rice husk and sugarcane residues. *Energy* **2012**, *37*, 177–184. [CrossRef]
98. Pulka, J.; Manczarski, P.; Stępień, P.; Styczyńska, M.; Koziel, J.A.; Białowiec, A. Waste-to-Carbon: Is the Torrefied Sewage Sludge with High Ash Content a Better Fuel or Fertilizer? *Materials* **2020**, *13*, 954. [CrossRef] [PubMed]
99. Kuzmina, J.S.; Director, L.B.; Shevchenko, A.L.; Zaichenko, V.M. Energy efficiency analysis of reactor for torrefaction of biomass with direct heating. *J. Physics Conf. Ser.* **2016**, *774*, 012138. [CrossRef]