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Organic Waste Torrefaction – A Review: Reactor Systems, and the Biochar Properties

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Abstract

Torrefaction is a thermochemical process in a narrow temperature ranging from 200 to 300°C, where primarily hemicellulose fibers are depolymerized. This process is carried out under atmospheric pressure and in anaerobic conditions; heating ratio is low (<50°C/min) and the residence time is relatively long, up to 1 h. During the process, a biomass is partially decomposed and forms different condensing and noncondensing gases. The final product is a constant substance rich in carbon, which is called a torrefied biomass—biochar and biocarbon. Currently an increase in energy demand is impacting the environment considerably. For this reason, in this chapter the organic waste torrefaction technology will be presented, including the reactor systems review. Torrefaction process may be conducted in different types of reactors, with diverse technologies. From this variety, two main groups of reactors can be distinguished, with direct and indirect heating. Direct heating group consists of reactors with multiple design, such as Multiple Hearth Furnace, microwave reactor, moving bed, vibrating belt, the reactor belt, and auger. Indirect heating reactors are less common and this group consists of rotating drum and auger reactor. All mentioned reactor types will be presented and discussed.

Keywords: organic waste, torrefaction, thermal treatment, biocarbon, torrefaction reactors

1. Introduction

Torrefaction is a biomass/waste thermal decomposition process that produces a carbon-rich product—Biochar [1]. Biomass partly decomposes during this process, generating both condensable and noncondensable gasses. The resulting product is a solid substance rich in

carbon, referred to as biochar, torrefaction biomass, or biocarbon [2]. In industry and literature, the torrefaction process is also referred to as roasting, slow and mild pyrolysis, wood cooking, and high-temperature drying [3].

Temperature and retention time are two main parameters that influence torrefaction process efficiency [4]. Torrefaction is usually conducted at temperatures between 200 and 300°C and the designated temperature is maintained for 15–60 min [5]. Choosing specific value of those two key parameters for different types of biomass is essential for cost-effective biomass treatment.

Torrefaction is a biomass treatment method for future utilization in cofiring in gasification process [3]. The process is commonly applied for lignocelluloses biomass treatment [6]. Lignocelluloses are built of three polymers: hemicelluloses, lignin, and cellulose. Hemicelluloses are the most reactive form of those three polymers, and their carbonization and devolatilization occur at temperatures below 250°C [6]. Vegetable biomass is used most commonly as the stock in torrefaction process. This biomass can be divided into two groups—green waste and energetic forestry products. Plants with the highest lignocelluloses percentage compared to sugars and fats have best energy potential [6]. Torrefaction feedstock used commercially or in research is mainly lignocellulosic (wood pellets or chips, crop residue, or tree bark) although organic nonlignocellulosic waste (bagasse from sugarcane industry, olive mill waste, poultry waste and litter, paper sludge, dairy cattle manure, or distillers grain) are being used more often [7].

Furthermore, all the considered biomass types are not just lignocellulosic by nature. Some waste biomass types, such as sewage sludge, digestate from biogas plants and agricultural animal waste, food waste, and spacecraft solid wastes (chemical composition of fecal simulant), consist of fats, proteins, and other organic matter, with very low lignocellulose content [7–9].

Due to the above studies, torrefied biomass/waste with very low lignocellulose wide-scale urbanization, production of such waste has increased substantially and the torrefaction process may help utilize this large volume of nonlignocellulosic biomass, including refuse derived fuel (RDF). The current absence of direct research in this particular area renders torrefaction decidedly underutilized.

Due to that, this technology is being found perspective, but the relation between process parameters, and biomass, and biocarbon properties should be still optimized. One of the methods is design and application of efficient torrefaction reactor.

Torrefaction process may be conducted in different types of reactors, with diverse technologies. From this variety, two main groups of reactors can be distinguished, with direct and indirect heating. The review of torrefaction reactor types will be presented and discussed.

2. Reactors classification

Torrefaction reactor can be divided into two main groups, based on the substrate heating—reactors with indirect and direct heating. Two subgroups can be distinguished in indirect

heating reactors group: auger and rotary type. Direct heating group may be divided because of the oxygen content in the heating medium into several subgroups: (1) the reactors in which the heating medium does not contain oxygen and (2) reactors wherein the heating medium contains a small amount of oxygen and other types (**Figure 1**).

The specific types of torrefaction reactors are described further.

2.1. Auger reactors

Auger-type reactor is constructed of one or more screw conveyors (auger). Its location relative to the ground may be vertical, horizontal, or at an angle. Biomass is fed to the reactor and then transported by a screw conveyor. During transport, the biomass is indirectly heated by a heating medium or directly by the heating elements located in the reactor wall. In both cases, there is a problem with uneven heating of biomass and excessive charring of the product. This phenomenon is linked to insufficient mixing of the substrate and local heating of the material [11, 12]. The residence time in the reactor depends on the length and speed of the conveyor.

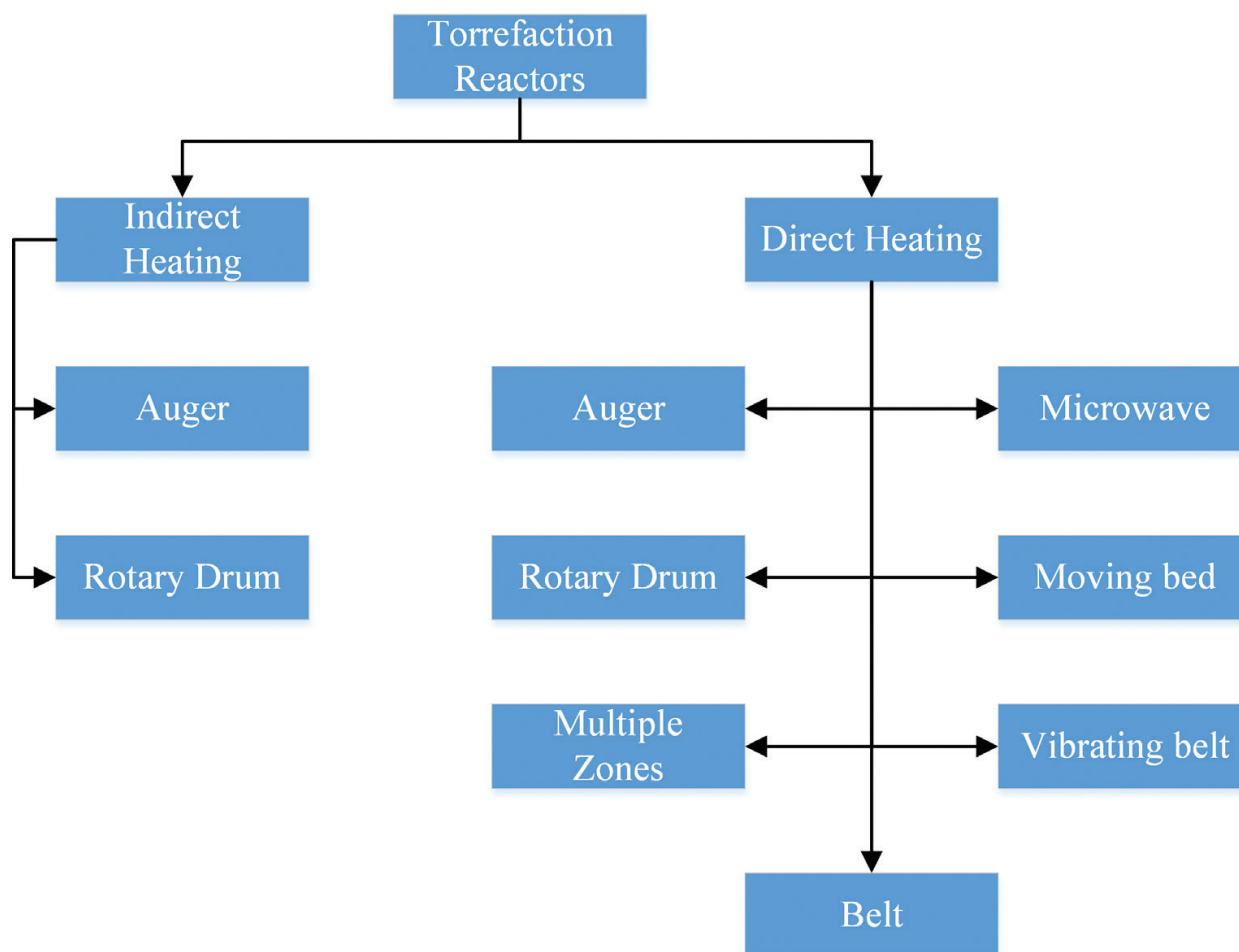


Figure 1. Torrefaction reactors division based on Ref. [10].

The advantage of auger-type reactors is their relatively low price, simplicity of adaptation to a large industrial scale, and low inert gas demand. The disadvantages include limited production capacity [11]. One example of the auger type reactor with indirect heating was described in patent published 15 October 2015 titled *Torrefaction plant, its operation and maintenance*. This design consists of five parts: feeder transporting a substrate, drying reactor, torrefaction reactor, ventilation and heating system, and auger. This reactor scheme can be seen in Ref. [13].

The material supplied for processing is fed to the feeding screw from where it is transported to the first reactor, where drying process is conducted. After passing through the first reactor, material falls by gravity into a second reactor, wherein torrefaction is carried out. At the end of the torrefaction reactor in the lower part, there is an opening that allows the material to fall on the conveyor transporting the product to the storage. Lower part of the reactor is equipped with rods that can be replaced when wear down caused by friction of the material during transportation. Auger transporting material inside the reactor for drying and torrefaction are powered by two independent electric motors (which can rotate in both directions). Conveyors drive shafts have been secured by a special latch (couplings), allowing quick removal of the tray in case of failure by inspection hatches located on the side of the engine.

The ventilation system for gases produced during the process is divided into two parts: an exhaust for gases discharge from the drying and torrefaction reactors. Gasses produced in the first process are not used due to the high moisture that affects its low calorific value. Torgas formed in the second reactor is purged of dust and partially of the condensate in cyclone, and is combusted to provide heat for the process (in the case of excessive production gas may be stored). Heating is indirect, provided by heat exchangers inside the reactor. Literature review shows that auger reactors with direct heating system does not differ significantly from the patent described above, due to that fact, their description is omitted. It is worth mentioning that torrefaction technology based on the chamber equipped with several screw conveyors that can create autonomous chambers or one large compartment can be seen [14].

2.2. Rotating drum reactor

Rotating reactor is a technology that allows for continuous operation without stoppage for loading or unloading. Process heat can be supplied directly or indirectly. In the first type, the heat is usually applied by the medium in the form of gas produced in the torrefaction process, which is recycled to the reactor and heated by the heat generated in the combustion of overabundance torgas. Direct heating is performed by the drum walls. Drum torrefaction reactors can be controlled by rotating speed adjustment or length and angle of drum inclination. The construction of the reactor ensures good substrate mixing, resulting in the uniform heating. This technology is simple and easy to scale. The disadvantages of such solutions include the production of a significant amount of fines that is formed by friction between walls and the substrate. Drum reactors also have a lower capacity than fluidized bed reactors, within the range of 1.5–4.5 mg·h⁻¹ [15]. In the literature and in registered technologies at the patent office, various torrefaction technologies using the drum reactor can be found.

Patented reactor by Teal W. B. and R. J. Gobel is equipped with screw conveyor or other mechanism for biomass feeding. The inlet is equipped with a gutter, followed by a single or double

lock. The lock is designed to prevent the oxidant penetration into the processing chamber during substrate feeding [15, 16]. The reactor heating system consists of three parts: a furnace, heat exchanger, and ventilation system. During reactor start-up, the fuel is supplied from the outside. Heat produced during combustion is used to warm up the air drawn from the outside, which is then transferred to a heat exchanger by a fan, positioned in front of the drum reactor. Heat is exchanged between the air heated in the furnace and the gas circulating in a closed circuit between the drum and the heat exchanger. Following a start up, the surplus torgas produced during torrefaction is burned inside the furnace. It is worth mentioning that biomass is heated before entering the drum reactor [15]. This reactor scheme can be seen in Ref. [16].

Main part of the reactor, the drum, rotates around its vertical axis. It is driven by the electric motor, which can be controlled to regulate the amount of drum rotation. Torrefaction chamber interior is equipped with a special blade to move or mix the processed substrate [16].

Behind the drum, there is a separator, which isolates biocarbon and torgas. Particles of biocarbon descend under gravity to the bottom of the separator and are disposed by screw conveyor or other transporting mechanism. In the bottom of the separator, valves are installed to prevent oxygen from getting to the system, which could adversely affect the process. Produced torgas from the separator is sucked by the fan and then directed to the combustion furnace or heat exchanger. Cyclone is installed before the fan to purify the gas from the fine particles and dust [16].

A. D. Livingston and B. J. Thomas registered patent proposing another drum reactor with indirect heating technology. Fuel delivery and its heating (ventilation inlets) differ this technology from the previously discussed reactor [17]. The biomass fed to the reactor first goes to the screw conveyor driven by an electric motor. This mechanism transports the substrate directly into the drum and in contrast to previous technology is not mixed with the heating medium.

The next element is a drum. In this case, it rotates inside a sealed casing and is driven by an electric motor. Shape of the blades responsible for moving and mixing of the material inside the process chamber differs from previous technology [17].

The system of heating the reactor operates in the same manner as in the first case. The difference is the method of heating medium delivery into the reactor chamber. Three air inlets were installed and located in the upper part of the drum casing. This reactor scheme can be seen in Ref. [17].

Output unit behind the drum acts as a gravity separator. The solid fraction falls to the bottom and the volatiles escape through a hole located in the top of the unit. Openings to receive the products are equipped with locks, tasked with preventing oxidant to enter the reactor. In addition, the separator is equipped with inspection doors, allowing reactor review without the demolition of the individual elements [17].

Direct heating reactor was divided into three parts: the substrate input, the drum reactor, and the products output, where the latter element is coupled with the reactor heating system.

Technical line begins with an airlock, which prevents air from entering into the reactor. Behind the latch, mechanical feeder is located for transporting the substrate into the process-

ing chamber. The next element is the drum, which is mounted on bearings, allowing its rotation. Rotation is provided by electrical motor. The drum itself is sloping toward the outlet end allowing material movement in its interior. The authors assumed that the reactor should be tilted by about $\frac{1}{2}$ inch per foot of the drum length. Collection of solid products takes place at the end of the reactor. Biochar falls by gravity to a conveyor installed at the end of the reactor through the rectangular holes.

The resulting exhaust gasses can be drawn through the ventilation system. The hood is positioned in the upper part of the back of the reactor forming a metal casing through which the process gases escape. This process is mechanical, powered with a fan. Produced gasses can be used for the purpose of the process. Ventilation system allows creating small vacuum for technological purposes.

A heating system is located in the rear part of the reactor. It consists of a rotary joint connecting the inlet and outlet of the reactor heating medium with the wires forming a heat exchanger inside the reactor (they are divided into sections and their number depends on the size of the reactor). The principle of the system is very simple. A heating medium which may be water, oil, propylene glycol, or other thermal transfer fluid is heated in a heating system to 315°C . Then, the medium is transported in tubes to the rotary coupling; there, depending on the size of the reactor, it is split into heat exchanger sections. The tubing forms a ring inside the drum and is attached to it in the front part of the reactor prior to the inlet of the substrate. Pipes forming a heat exchanger are equipped with thermal expansion joint in order to prevent damages during operation. The liquid after transferring heat to the reactor is recycled to the rotary coupling and then to the heating system where the cycle begins again [18]. Schematic drawing of inlet, outlet, and reactor heating systems is shown in Ref. [18].

2.3. Multiple Hearth Furnace

Multiple Hearth Furnace technology is used on an industrial scale because it scales easily, and it can be adjusted to the individual preferences of the customer. Also, it provides stable process temperatures, mixing of substrate, and leak free gas flow. The disadvantages of this technology should include slow heat transfer to the substrate, compared to other direct reactors, the limited volume of the converted substrate, which results in larger dimensions of the reactor and requires good seal of the shaft [15]. Multiple hearth torrefaction reactors do not differ significantly from each other. Design differs mainly on configuration of heating and ventilation system, and therefore, one design will be presented to describe the principles of this technology. Multiple hearth reactors are cylindrical, and their interior is divided into multiple levels formed of trays which are fixed to the centrally placed shaft which rotates about an axis of symmetry. It is driven by a motor with a built-in gearbox. The substrate is fed to the reactor from above by a mechanical conveyor, equipped with airlock located at the end of the conveyor, preventing oxidant from entering the reactor. Biomass can be predried in a separate drying system. In this case, the reactor has only a section in which the torrefaction process occurs. If separate drying system is not installed, the reactor is divided into a drying and torrefaction section [19, 20].

The substrate supplied to the first level begins to be heated and distributed evenly using a roller located over the tray. After one full rotation, overabundant biomass is pushed by the roller to the hole where it falls by gravity to the lower level and the process begins again.

The product is collected at the bottom of the reactor and goes to the cooling system. Heating system can be divided into two types depending on whether the reactor has a drying zone. In the first case, the heat is supplied with heated gas into the drying and torrefaction zone independently. Reason behind this design is that during the process of drying, the moisture contained in the biomass evaporates, hence decreases the gas calorific value (the resulting gas is not suitable for energy production). After heating medium passes through the drying zone, excessive gas is released to the atmosphere, and the remaining volume is returned to the heat exchanger for reheating and back to the reactor. Torrefaction zone is heated in the same way as described above with the difference that the overabundant gas formed in the torrefaction process is used as fuel to provide the heat for the process [19, 20]. Reactors with only torrefaction zone are heated by the heating medium consisting of inert gases circulating in a closed loop between the reactor and the heat exchanger—same design as a two-zone reactor. Excessive gas is used for the purposes of the process as a fuel [19].

2.4. Microwave reactor

In this type of reactor, the heat is provided by microwave radiation. This technology is characterized by rapid and uniform heating of the material. The process duration depends on the type, size, and microwave radiation absorption capacity of the processed material and on the reactor power [15]. The main problem with this technology is the high energy consumption required for the production of microwave radiation. Torgas is not used for process purposes and it adversely affects the process efficiency and increases the operation costs [12]. Technology shown in patent titled *Microwave torrefaction of biomass* schematically illustrates a microwave reactor, wherein the authors indicate that besides torrefaction, other processes like pyrolysis and gasification can be performed. Technological line starts from the biomass storage, where material grinding (hammer mills are used most often) and drying occurs. The heat for the drying process is supplied from the heat exchanger located at the end of the process line responsible for the cooling of the product [21]. Behind the hopper, there is a biomass powder compacting device to form pellets or briquettes, which are then collected by a screw conveyor that acts as a process chamber. The front part of the conveyor is also equipped with an inlet of inert gases to ensure anaerobic conditions. Patent authors suggest that the feeding screw should have cylindrical shape with a constant diameter of not more than 50 cm (optimum diameter is in the range 0.5–10 cm) to ensure uniform biomass radiation. The length of the reactor depends on the process parameters, including the diameter of the substrate, feeding rate, the microwave energy, and the numbers of microwave radiation points. The process chamber is equipped with volatile components outlet located at the top and resulting liquid products outlet located at the bottom. Screw conveyor is surrounded by a microwave chamber, which should be equipped with at least one source of microwave radiation. Number of sources depends on the reactor size and process parameters [21]. Screw conveyor is longer than the microwave chamber. Behind the microwave chamber, there is a cooling section of the

solid product. Heat is received by a heat exchanger and is used for biomass drying. Diagram of the technological system is shown in Ref. [21, 22].

2.5. Moving bed

The reactor consists of a closed process chamber, where biomass is fed from the top. The reactor has no moving parts, responsible for moving the biomass that falls down freely during the process. The substrate is heated by a heating medium, a gas that has an inlet located at the bottom part of the reactor. Torgas outlet is located at the top of the chamber. Single cycle duration range from 30 to 40 min, and the maximum temperature that can be obtained is 300°C [12]. Simple design, high bed density, and a good heat transfer are main advantages of this design. Difficulty of controlling the temperature and maintaining heating medium pressure are clear disadvantages of this technology [15].

2.6. Vibrating belt

The main part of the reactor is a vibrating belt that is responsible for biomass transporting. Flow rate of the substrate is controlled by intensity of vibration. Biomass is heated indirectly by the gaseous heating medium [12].

In order to standardize the resulting product, reactor has many levels. The advantages of this type of reactor include simplicity of process time adjustment and the possibility of converting the biomass of larger dimensions. Clogging of the apertures with tar and dust generated during the process (cleaning of the reactor is associated with a long maintenance brake, since it must be disassembled) is a main disadvantage. Temperature control of the process is difficult, because it must be correlated with flow of the heating medium and the intensity of the vibration. These reactors require a large space, which also causes problems with their use if space is limited. High risk of corrosion is also associated with this design [12].

2.7. The belt reactor

Presented torrefaction belt reactor consists of four parts: feeder, the reactor chamber with conveyor belts, screw conveyor, and the heating system [23]. This reactor was presented in Ref. [23].

The biomass supplied to the reactor with conveyor goes into the torrefaction chamber, wherein three conveyor belts segments are located. Each of the conveyors is rotating in the opposite direction as the previous one in order to transport the substrate to the bottom of the reactor. Torrefaction chamber is heated directly using a heating medium, produced during the combustion of torgas or the fuel supplied from the outside. The temperature inside the chamber does not exceed 800°C and is controlled by the volume of injected heating medium. Process chamber is equipped with heating ducts, which have been separated from the gas space of the reactor in order to prevent mixing of heating medium and torgas. After the process, biomass goes to the chute located at the bottom of the reactor and then is received by the externally cooled screw conveyor.

Reactor production capacity range from 100 to 500 kg h⁻¹, and the plant can operate in temperature range 220–350°C.

3. Survey of existing installations

Reactors technology described above has been applied on an industrial scale. There are more than 50 companies involved in the implementation of torrefaction technology [12]. **Table 1** shows the characteristics of said technologies.

Developer	Technology	Heating mode	Capacity, mg·h ⁻¹	Country
4 Energy	Belt conveyor	Direct	5.5	The Netherlands
Agritech	Screw conveyor	Indirect	8	USA
AIREX	Cyclonic bed reactor	Direct	0.25	Canada
Atmoclear	Belt	Direct	5	UK
Bio Energy Development North AB	Rotary drum	Direct	3.5	Sweden
Biolake	Moving bed	Direct	5	The Netherlands
BTG	Screw conveyor	Indirect	5	The Netherlands
CanBiocoal	Microwave	Direct	12	UK
EBES	Rotary drum	Direct	1.5	Germany
ECN	Moving bed	Direct	5	The Netherlands
Earth Care Products	Rotary drum	Direct	1.5	USA
ETPC	Rotary drum	Indirect	4.3	Spain
Foxcoal	Screw conveyor	Indirect	4.2	The Netherlands
Horizon Bioenergy	Oscillating belt conveyor	Direct	6.5	The Netherlands
IDEMA	Moving bed	Direct	2.5	France
Integro	Multiple hearth	Direct	2	USA
New Biomass Energy	Screw reactor	Indirect	5	USA
New Earth	Oscillating belt conveyor	Direct	2	USA
RFT	Screw conveyor	Indirect	5	USA
Stramproy	Oscillating belt conveyor	Direct	5	The Netherlands
Thermya/LMK Energy	Moving bed	Direct	2.5	France
Topell	Torbed	Direct	8	The Netherlands
Torr-coal	Rotary drum	Indirect	4.5	The Netherlands
West Creek Energy	Rotary drum	Direct	10	USA
WPAC	Unselected	Unknown technology	5	Canada

Table 1. Survey of existing installations based on Refs. [12, 15].

4. Product characteristics

Torrefaction products (biochar and biocarbon) can be characterised by specific properties. Biochar has high energy density, it contains 80–90% of potential energy, while decreasing its mass to 70–80%, hence energy density can be increased by 30% [24]. Biochar does not absorb moisture or its equilibrium moisture contents drop to 1–3%, thus it can be described as hydrophobic [6]. Fixed carbon content increases during the process, depending on process parameters (temperature and duration), values ranged between 25 and 40%, making biochar a potentially attractive reducing agent [24]. Torrefaction reduced oxygen content significantly, thus reducing O/C ratio, this makes biochar attractive substrate for gasification [6]. Mechanical processing (grindability and palettization) of biochar improves significantly. The output of a pulverizing mill can increase by 3–10 times [25, 26] comparing it to a raw biomass. Torrefied biomass takes less time to ignite due to lower moisture and it burns longer due to larger percentage of fixed carbon compared to raw biomass [27].

Typical lower calorific value (LCV) of biocarbon from lignocellulosic biomass (LB) wood chips—torrefaction ranges between 18 and 23 MJ/kg [27]. Due to low biocarbon moisture (1–6%), the difference between higher calorific value (HCV), and LCV is small [28]. LB biocarbon has relatively low bulk density 180–300 kg/m³, it is fragile and homogenous [29]. Additional advantage of LB biocarbon is its hydrophobic nature. The absorption of water by torrefied biomass is strongly limited by dehydration processes during thermal decomposition of organic matter. Destruction of OH– groups causes the inhibition of formation of bonds between water and hydrogen. Therefore, biocarbon may be a storage outdoor without risk of biological decay. Torrefaction of LB brings benefits in biocarbon incineration, due to decreasing ignition temperature and shortening the time of ignition [30]. Additionally, many researchers [24, 27, 31] proved that during torrefaction, biocarbon retains potential energy (around 90%), while decreasing substrate mass to 70–80%. All of these properties make biocarbon a desirable fuel for processes like incineration, co-combustion, and gasification.

Another possible pathway is to recycle biocarbon from LB and nonlignocellulosic biomass (NLB) for improving soil properties agent by its application on weak soils (arable and forest) and on the former land after mining of aggregates such as sand or gravel. Soil deposit of biocarbon from lignocellulosic crops (biological coal) according to many research reports has been considered as the method of effective soil improvement and significant element of carbon sequestration in the process of climate change mitigation [32, 33]. It is known that beneficial effect of biocarbon on soil properties is caused by improvement of soil texture, porosity that reflects in modifications of many physical and chemical properties, and soil biology. But simultaneously, the processes of biochar decomposition and impact on soil biology are fragmented and require closer research attention.

Dissolved organic matter is a labile fraction, which can rapidly respond to changes in carbon pools, as they are potentially easy-mineralizable. These labile parts of organic carbon have been suggested as sensitive indicators of soil organic matter changes and important indicators of soil quality [33]. Mineralization of organic carbon compounds promotes the release of carbon dioxide into ambient air as one of greenhouse gases (GHG). Most “active” and

susceptible to transformations form of soil organic carbon (SOC) is labile organic carbon. Soil labile organic carbon (SLOC) is composed of amino acids, carbohydrates, microbial biomass, and other simple organic compounds [34]. SLOC is cycling fast in the environment [35]. Circulation of SLOC lasts for not more than several years, while the refractory carbon cycle may last even several thousand years [35]. Soluble carbon and nitrogen are important, as they have a great impact on dissolved organic fraction concentrations in freshwater [36]. Hot water-extractable carbon is the fraction of organic matter, which is naturally labile and its content is correlated with the mass of microorganisms simultaneously being an excellent indicator of qualitative changes in organic matter [36]. This fraction is potentially the most susceptible to oxidation of CO₂ [33], and therefore has the greatest impact on global climate change.

Introducing biocarbon into soil causes decrease of solubility of SLOC and finally decreases the GHG emission. Therefore, the interesting aspect of biocarbon recycling into soil is proposed in this project examination of GHG emissions from soil enriched biocarbon and the degree of pollutants elution form biocarbon including organic compounds and heavy metals.

Biocarbon has heterogeneous highly porous structure and its outer and inner surfaces are very big and have a lot of “niches” of different water properties – hydrophilic and hydrophobic of basic and acid reaction etc. It makes biochar important in water holding capacity, which is especially an important treatment on weak soils. Thanks to stable nature of biocarbon (with half-lives estimated in broad ranges from hundreds to thousands of years); the positive impact of biochar may be prolonged for years. In this context, it is also important to build the knowledge on long term impact of biochar on groundwater. Méndez et al. [37] examined the influence of biocarbon obtained from sewage sludge on plants. The concentration of copper in biocarbon was about 80% higher than in raw sewage sludge and about 40% in case of other heavy metals, but their bioavailability and mobility were significantly lower. The increase of torrefaction temperature caused the increase of heavy metal content in biocarbon, but their bioavailability and mobility decreased. Authors determined also that within the increase of temperature up to 300°C, the content of nitrogen slightly increased, but levels of P and K were constant. Presented data indicate that also in NLB torrefaction, it is possible to generate biocarbon with valuable properties.

5. Summary

Given torrefaction reactors review showed a variety of technical and technological solutions. Most of the differences are related to material flow through reactor, material heating mechanism, the source of heat for the process, and torrgas treatment. As the torrefaction process is classified between high temperature drying and low temperature pyrolysis, most reactor systems are similar to those commonly used in biomass/waste drying, and/or pyrolysis. Actually, it is difficult to distinguish a specific type or solution of the reactor, which would be a characteristic only for torrefaction. Therefore, it seems that application of torrefaction of some biomass may be easily implemented just by adaptation of pyrolysis reactors. The problem may be related to torrefaction energy balance due to relatively low calorific value of torrgas

or problem with mechanical movement of the feedstock through the reactor caused by friction and/or melting of such materials like plastics.

Each presented reactor type has its advantages and disadvantages. Some are cheap, easy to construct, and operate. Some have problems with material mass flow, heat flow. Some are good for laboratory test, but some may have potential for industrial purposes. At this stage of the torrefaction technology development, it is hard to specify which type of reactor should be recommended. The torrefaction may be dedicated for different types of biomass and waste. The choice of torrefaction reactor should be based on the biomass/waste type and properties, the components of energy balance, pollution degree of the torrgas, desired biocarbon properties, energy demand, economy, and the current situation of the biomass/waste, and biocarbon utilization market. The torrefaction technology is relatively new and it is perspective. Not all problems have been solved, yet. Many new ideas arise each day at this field. Therefore, there is a room for innovations and inventions, which may move the torrefaction technology at the higher level of development. Intensive research and development activity in this field is then required and justified.

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