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Review

Future Perspectives of Biomass Torrefaction: Review of the Current State-Of-The-Art and Research Development

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Abstract: The growing search for alternative energy sources is not only due to the present shortage of non-renewable energy sources, but also due to their negative environmental impacts. Therefore, a lot of attention is drawn to the use of biomass as a renewable energy source. However, using biomass in its natural state has not proven to be an efficient technique, giving rise to a wide range of processing treatments that enhance the properties of biomass as an energy source. Torrefaction is a thermal process that enhances the properties of biomass through its thermal decomposition at temperatures between 200 and 300 °C. The torrefaction process is defined by several parameters, which also have impacts on the final quality of the torrefied biomass. The final quality is measured by considering parameters, such as humidity, heating value (HV), and grindability. Studies have focused on maximizing the torrefied biomass' quality using the best possible combination for the different parameters. The main objective of this article is to present new information regarding the conventional torrefaction process, as well as study the innovative techniques that have been in development for the improvement of the torrefied biomass qualities. With this study, conclusions were made regarding the importance of torrefaction in the energy field, after considering the economic status of this renewable resource. The importance of the torrefaction parameters on the final properties of torrefied biomass was also highly considered, as well as the importance of the reactor scales for the definition of ideal protocols.

Keywords: renewable energy; biomass; torrefaction; grindability; rotary reactor

1. Introduction

Currently, fossil fuels, such as oil, natural gas, and coal, represent the primary energy sources existent on the planet. However, these resources are limited and their shortage is predicted for the next 50 years [1–5]. Other than their potential shortage, fossil fuels contribute considerably to negative environmental impacts. Therefore, reductions in carbon dioxide (CO_2) emissions, one of the main gases responsible for greenhouse effects (GHG), through the use of renewable energy sources, is a main target, with goals to reduce GHGs emissions from 1990 to 2030 by 40% and to reduce GHGs emissions by 80–95% by 2050 [5–9].

With the advent of the concept of sustainability, the idea of using natural resources to meet the needs of the present without compromising on the satisfaction of future needs has become a first priority [10–12]. One of the mechanisms developed for better conservation efficiency is the use of renewable energy sources that have little or no direct impact on the environment. The use of renewable energy is important because of the economic factor, where the use of cheaper resources for energy production favors the preservation of the environment, since most use natural, abundant, and reusable means for the production of electric energy [13–15]. The demand for ecologically acceptable substitutes for fossil fuels has been accelerated both by increasing the use of renewable energy sources and by predicting the declining supply of non-renewable energy. Biomass is considered the oldest energy source, and its energy (bioenergy) is becoming more and more promising due to a set of characteristics that allow the substitution of fossil fuels, thus, reducing GHG emissions [16–18].

The composition of biomass includes cellulose, hemicellulose, and lignin, thus, comprising of these main components and other organic and inorganic components, such as minerals, that are present in lower quantities [19]. The mass percentages of the three main components of biomass depend on its origin [20]. Due to their different structural compositions, cellulose and hemicellulose have different behaviors during thermal decomposition. In general, the thermal decomposition temperature (TDT) of hemicellulose is smaller, occurring in temperatures between 220 and 315 °C whereas cellulose decomposes between 315 and 400 °C. Lignin has a more gradual thermal decomposition, with its TDT fluctuating between 160 and 900 °C [20]. Biomass derived energy can be used directly, but can also be converted to a secondary energy resource through a chain of thermal and biochemical processes, such as gasification, torrefaction, liquefaction, pyrolysis, anaerobic digestion, fermentation, and transesterification [2,16,21].

Some of the problems associated with the energy production of biomass in its original form when in comparison with fossil fuels are its lower density, higher moisture content, and hydrophilic nature, which cause its HV to decrease, making it difficult to use biomass for large scale productions [3,22,23]. All these parameters influence the logistics of the energy production process using biomass, as well as its energetic efficiency [24].

Torrefaction is one of several processes of biomass improvement, thus, modifying it physical and chemical composition. This process consists of the slow heating of biomass through a range of temperatures between 200 and 300 °C in a controlled atmosphere without the presence of oxygen (O), [24]. Torrefaction enhances the performance of biomass during co-combustion and gasification [25–27].

Presently, there are several studies regarding the effects of different torrefaction parameters on the final physical and chemical composition of biomass for energy production [2,22,24,28].

There are also innumerous studies showing the importance of laboratory scale reactors for the development of ideal protocols to mimic when using other scales, such as pilot and commercial. Laboratory scale reactors are considered the most important due to their price, which is considerably lower than in other scales, allied with the fact that this scale is enough to define the right parameters to use even when applying them to different scales [29].

In this article, such studies are summarized and reviewed to study the concept of torrefaction and the current and innovative attempts to improve the outcomes of this process, specifically, the quality of torrefied biomass using different techniques and the different sources of raw biomass.

2. Torrefaction Process

As was previously mentioned, torrefaction (specifically, dry torrefaction) consists of a thermal treatment of biomass, where biomass is heated in a non-oxidizing atmosphere to improve the biomass' energy density through the increase of its HV and hydrophobicity [16,30–32].

Taking into account a more chemical approach, the principle of this process rests on the removal of oxygen (O) and hydrogen (H), with the production of a final solid product with lower oxygen-carbon (O/C) and hydrogen-carbon (H/C) ratios as shown in Figure 1 [2,33].

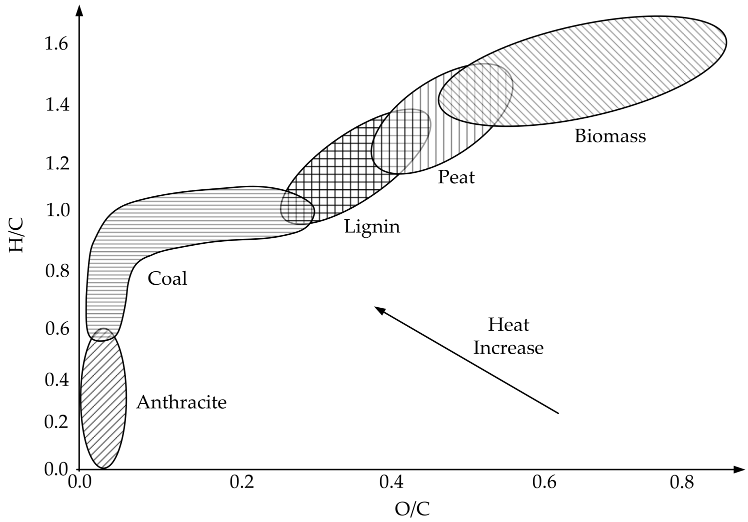

Figure 1. van Krevelen diagram (adapted from [33]).

Several studies have proven that after the torrefaction process, biomass properties are extensively modified and improved [2,34–37].

This type of thermal treatment not only destroys the fibrous nature of biomass and, consequently, its tenacity, but also increases its HV [2,16]. Torrefaction also increases the hydrophobicity of biomass, which means that biomass becomes more resistant to water adsorption, resulting in an improvement in the control of storage conditions due to the fact that torrefied biomass is more resistant to bacterial and fungi attacks, and, thus, more resistant to rotting [2]. During its torrefaction, biomass suffers mass loss, maintaining, however, its energy yield [19].

Other properties, such as O/C and grindability, allied with the fact that the characteristics of torrefied biomass are more uniformly distributed, make biomass more appealing when compared with non-torrefied biomass, as can be observed in Figure 2 [16].

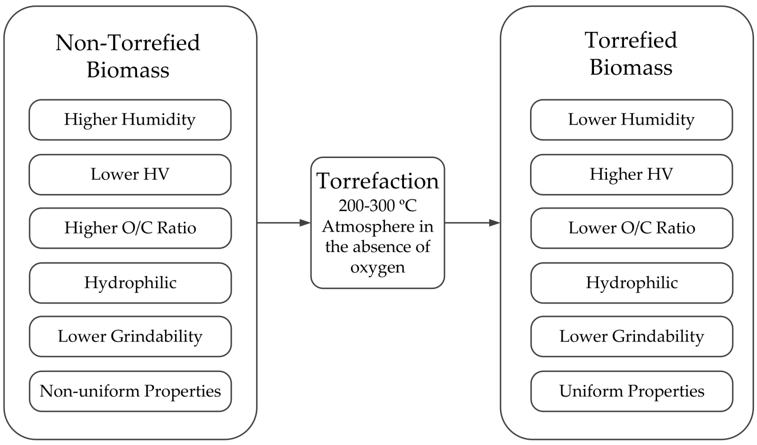

Figure 2. Schematic representation of biomass characteristics compared with torrefied biomass characteristics.

2.1. Torrefaction Process

The torrefaction process (dry torrefaction) can be divided into distinct phases: Heating, drying, torrefaction, and cooling [2]. According to Bergam et al. (2005), the drying process is subdivided into two phases, making torrefaction a process comprised of five different phases, as explained in Table 1 [38].

Table 1. Description of the different torrefaction phases (adapted from [38]).

Phases	Description
1. Heating	Biomass is heated until the drying temperature is obtained and the biomass' humidity starts to evaporate.
2. Pre-drying	Occurs at 100 °C when the free water present on biomass evaporates at a stable temperature.
3. Post-drying	The temperature is increased until it reaches 200 °C. The remaining water present on biomass chemical bonds is completely evaporated. This phase is responsible for mass loss due to the evaporation of several biomass components.
4. Torrefaction	Main phase of the torrefaction process. It occurs at 200 °C and is responsible for the main mass lost. The torrefaction temperature (TT) is given by the maximum stable temperature used during the process.
5. Cooling	The final product is cooled down to a temperature below 200 °C, which is the temperature of wood auto-ignition, before it contacts the air and until room temperature is reached.

Figure 3 represents the different stages of biomass heating during the torrefaction process, starting at room temperature until the TT is reached (T_{tor}), followed by cooling.

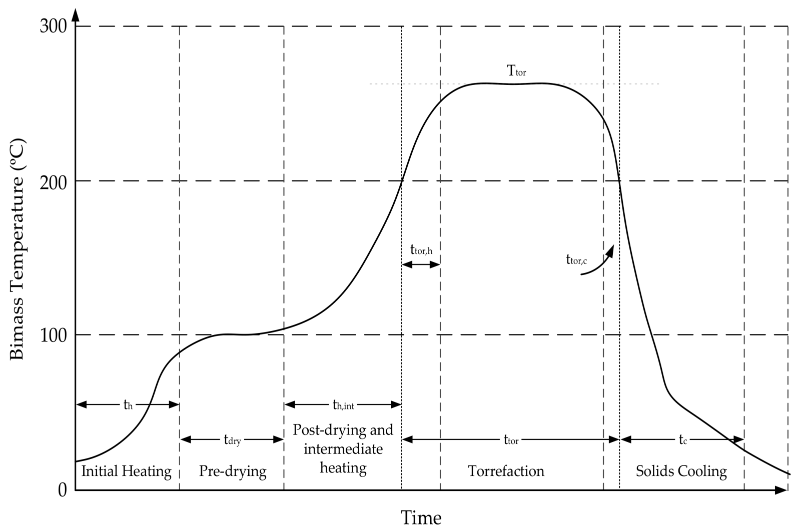

Figure 3. Schematic description of the different torrefaction stages (adapted from [38]). Where t_h represents the time for drying to start; t_d represents the time for drying; $t_{h,int}$ is the intermediate heating time from drying to torrefaction; t_{tor} is the reaction time at the desired torrefaction temperature, T_{tor}; $t_{tor,c}$ is the cooling time from the desired T_{tor} to 200 °C; and t_c is the cooling time to room temperature.

2.2. Parameters that Influence the Torrefaction Process

There are a wide range of parameters that influence not only the torrefaction process, but also the final product characteristics. These parameters include the temperature and residence time, heating rate, operating atmospheric composition, controlling of the torrefaction process instability, and the type of reactor.

Although there are not many studies regarding the optimization of such parameters, the ideal process would be determined by their combination, while trying to maximize the quality of the torrefied biomass production, depending on the type of biomass in use [38,39].

2.2.1. Temperature and Residence Time

The perception of biomass components, as well as it chemical composition, enables the study of biomass behavior during the heating processes [22]. The exposure of biomass to high temperatures leads to thermal degradation of it physical structure and, thus, to mass loss. The degradation of biomass depends on the duration of heating and the maximum temperature obtained [40]. The different components of biomass have distinct characteristics and, therefore, behave in various ways, depending on their origin, and also interact differently depending on the thermal process and its temperature [22].

Other variables that influence the torrefaction process also take part in the changes that occur to the composition and structure of biomass, such as particle size, heating rate, and pressure [41].

Residence time mainly affects the decomposition of hemicellulose, whereas cellulose loses mass depending on the reaction time [38].

The final product characteristics are more affected by temperature than residence time. Temperature defines the kinetics of the torrefaction reaction while residence time affects process characteristics, but only during some temperature ranges [42,43].

2.2.2. Heating Rate

The heating rate (°C/min) used during the torrefaction process influences the secondary degradation reactions, which affect the final solid, liquid, and gas product distribution ([44], 2018).

Strezov et al. observed that the energy yield of liquid pyrolysis of *Pennisetum purpureum* is higher when the heating rate is also higher whereas coal does not suffer any changes. The main reason for the distribution of reaction products is the reduction of the number of secondary reactions when using higher heating rates [45].

Kumer et al. also suggested that by increasing the heating rate, there would be a reduction of the effects of heat and mass transfers between particles [46].

2.2.3. Operating Atmospheric Composition

The torrefaction process can be affected by the gas flow used during the process [47]. This occurs due to the secondary interactions between the gases of the torrefaction process, such as water vapor, air, and other atmospheric compounds [48].

According to several studies, carbon monoxide (CO) is the main gas released during the torrefaction process and it is formed during a secondary reaction between water vapor (H_2O (g)), CO_2 and solid torrefaction products when the temperature increases [42,43]. The minerals present in biomass can also serve as catalysts for this reaction [44], hence, the ratio between CO_2 and CO decreases with a higher residence time [42,43].

There are no substantial changes in biomass reactivity depending on the O_2 presence in the atmosphere, nor substantial changes in the solid reaction products [49].

2.2.4. Controlling Torrefaction Process Instability

Temperature is one of the most influential parameters of the torrefaction process and, therefore, the most substantial to control. There are some difficulties associated with controlling the torrefaction process' temperature, which influences the inertia of the process, making it faster or slower. To maintain the quality of the final torrefaction products, it is of essence to keep temperature conditions as stable as possible [44].

It is also important to consider that, during the torrefaction process, the emission of volatile compounds, both non-condensable and condensable, occurs. In case their removal does not occur, especially the removal of condensable products, the cooling process will promote the formation of tar and other hydrocarbon-based compounds that can interfere with the self-ignition of torrefied biomass due to their low ignition temperature [44].

Condensable compounds originate from biomass with higher contents of condensable materials. One solution for this problem would be the implementation of a pre-treatment protocol for biomass to reduce the compounds released during the torrefaction process [44].

2.2.5. Type of Reactor

Using green biomass for combustion processes has many disadvantages, such as its instability during this process due to the humidity and size of the reactor chamber [29].

The types of reactors used can have three distinct scales: Pilot, commercial, and laboratory [29].

The laboratory scale reactors are considered the most important reactors for the development of studies to test parameters of the torrefaction process for later applications on the pilot and commercial scales [50]. This type of torrefaction reactor can be subdivided into four types: (i) Fixed bed torrefaction reactor, (ii) microwave torrefaction reactor, (iii) rotary drum reactor, and (iv) fluidized bed torrefaction reactor [29].

(i) Fixed bed torrefaction reactor

The fixed bed torrefaction reactor is considered the simplest reactor. The fixed amount of raw biomass is filled inside the reactor and is heated by heat conduction from the electrical heater around the surface of the reactor [29].

(ii) Microwave reactor

The microwave torrefaction reactor uses high frequency electromagnetic waves, namely microwaves. These microwaves create a vibration of water molecules inside the biomass, resulting in an increase of its temperature. Wang et al. constructed and tested the microwave reactor in [51].

(iii) Rotary drum reactor

The rotary drum reactor is the most common type of reactor, which could be directly and indirectly heated and can be observed in Figure 4. The rotary drum reactor is a continuous reactor and process that can be considered a proven technology for a wide range of applications. This type of rotary drum is constructed in such a way that it can receive biomass near the inlet end and displays a discharge port near the outlet end. In the case of torrefaction, the biomass in the reactor can be heated directly or indirectly with superheated steam or exhaust gas that is produced by the combustion of volatile organic compounds (VOCs). When the process of torrefaction ends, the torrefied biomass is then discharged from one or more ports on the shell of the drum [52,53].

(iv) Fluidized bed torrefaction reactor

The raw biomass is placed on a grate and the hot inert gas flows from the bottom through the raw biomass bed. At a suitable inert gas velocity, the raw biomass floats and behaves like a fluid. This results in a uniform temperature distribution throughout the raw biomass bed [54].

Although there are many types of reactors, further research regarding the ideal reactor design for minimum energy use are mainly concentrated on laboratory scale reactors due to the reproducibility of these reactors to a pilot and commercial scale [29].

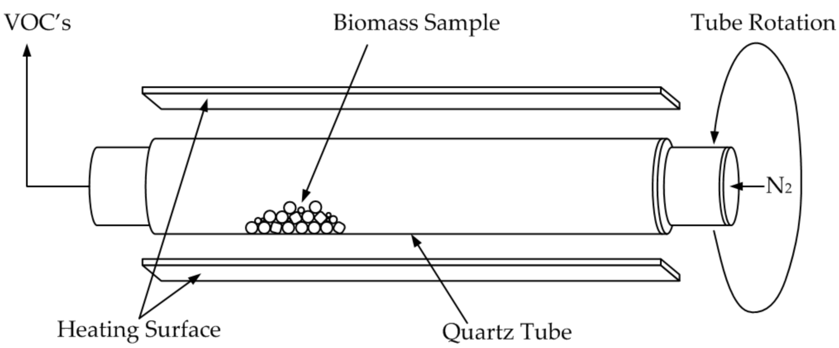

Figure 4. Diagram scheme of the laboratorial NABERTHERM rotary reactor [53].

3. Torrefied Biomass

3.1. Properties of Torrefied Biomass

As previously mentioned, torrefaction modifies certain properties of biomass, making it more appealing than non-torrefied biomass [16]. The most significant properties are the moisture content, bulk density and energy density, grindability, particle size distribution, sphericity and specific surface area, and the heating value [16,22].

3.1.1. Moisture Content

Normally, the moisture content of non-torrefied biomass ranges from 10–50%. However, since torrefaction is a process that occurs at high temperatures, including phases with specific biomass drying, the moisture content of the non-torrefied biomass is reduced to about 1–3% [22]. This is an important parameter to consider as high moisture content translates into energy loss when burning biomass [16]. Therefore, to increase energy efficiency and the quality of the final product, it is necessary to reduce its moisture content by reducing emissions during the thermo-chemical process of energy conversion [55].

Reducing the humidity of the biomass has many positive consequences in relation to its transport and storage, since, thanks to its low water content, it becomes lighter and less susceptible to rot [56].

During the torrefaction process, the hydroxyl groups present in wood are partially destroyed by dehydration, which prevents the formation of hydrogen bonds, causing the torrefied biomass to become hydrophobic [25].

3.1.2. Bulk Density and Energy Density

The loss of mass in the form of solids, liquids, and gases during torrefaction of the biomass causes an increase in the porosity of the same. This results in a significant decrease in the volumetric density of the biomass, usually ranging from 180 to 350 kg/m^3, depending on the initial density of the non-torrefied biomass [16]. Despite this decrease in bulk density, the energy density of the torrefied biomass increases after torrefaction (±30% increase) [25].

3.1.3. Grindability

Biomass is extremely fibrous and tenacious. During torrefaction, biomass loses its toughness, mainly due to the destruction of its hemicellulose matrix and cellulose depolymerization [16], which leads to a decrease in the length of their fibers. The length of each particle also decreases without changing its diameter, which results in better grinding characteristics, handling, and greater creep during processing and transport [22].

These changes in biomass microstructure increase the mass percentages (wt.%) of the fine particles, subject to the same grinding conditions [1,57].

There is also a 90% decrease in energy consumption for the grinded torrefied biomass chips compared to non-torrefied wood chips [58].

3.1.4. Particle Size Distribution, Sphericity, and Specific Surface Area

Parameters, such as particle size distribution curves, sphericity, and specific surface area (SSA), are crucial parameters in the perception of creep and behavior during the co-combustion of the torrefied biomass [16,28]. Recent studies show that torrefaction of biomass allows the formation of narrower particles, resulting in more uniform sizes, which is a characteristic similar to coal. Authors, such as Phanphanic et al. (2011), observed that the particle size distribution curve for torrefied biomass has its maximum distribution along smaller sizes as the torrefaction temperature increases [58].

As for sphericity and SSA, these are also two parameters significantly affected by torrefaction. According to Phanphanic et al., from 300 °C the sphericity and SSA values also increase [58].

3.1.5. Heating Value

The amount of H and O lost by the biomass during the torrefaction process is higher than the amount of C lost by it, which causes an increase in the heating value of the torrefied biomass [59]. The HV of the torrefied biomass is higher than that of the non-torrefied biomass, since there is an increase of the fixed carbon, in contrast to the output of the oxygen compounds, leaving more carbon available to be oxidized and thus to release energy [22].

4. Economic and Social Analysis

Due to the biomass properties which allow it to be used preferentially in relation to fossil fuels, since it is not only renewable energy but also its CO_2 emissions balance is neutral, it is considered to be the fourth primary source of energy used in the world [60].

As already mentioned, torrefaction is a process of improving biomass properties to form a more homogeneous product, which is densified through palletization, resulting in biomass with a higher HV and energy—Torrefied pellets (TOP's, according to ECN; or TBP's, according to [24]), which have properties very similar to those of coal [61]. In this way, torrefied biomass has a wide range of potential uses in industries where coal is typically used as an energy source [62].

The increasing interest in biomass and, consequently, its demand, causes an increase in the price of most biomass fuels for conversion into thermal energy [36].

Several studies suggest that biomass plantations in developing countries can contribute, in the long term, to increased biomass production. However, other authors suggest that this contribution of biomass is minimal [44].

In any case, these plantations are important and, therefore, it is necessary to consider factors, such as the availability of soil and yield of biomass production among other parameters, such as the climate and types of soil [63].

Despite the potential of biomass to replace fossil fuels, there is a risk that its planting will affect ecosystems by creating negative impacts on the quality of water and soil and affecting food chains [64]. Another potential consequence of biomass production is its overproduction, which leads to deforestation and a consequent decrease in biodiversity [65].

Radics et al. concluded that the profitability of making torrefied pellets essentially depends on sale prices and feedstock costs. However, the costs associated with a scale-up and long-term operations are still very uncertain [66]. This is one of the reasons why laboratory scale reactors pose such an important role in developing torrefaction protocols.

5. Analysis of the Research Literature

Torrefaction is a slow and low temperature pyrolysis process that is not very different from the one used in charcoal production cells, which were used as a reducing agent in the earlier stages of metallurgical processes at the beginning of the industrial revolution. However, the development of the torrefaction process only began with the production of coffee in the late nineteenth century, as documented in the first patents of Thiel (1897) [67] and Offrion (1900) [68]. Other patents in the area of torrefaction were patented in the following years and can be seen in Table 2.

Table 2. Other patents in the area of torrefaction and their respective period of patenting.

Period of Time	Number of Patents
1922–1925	3
1930–1932	3
1939–1952	10

Some research on torrefaction, still in the 1930s, was devoted to the production of gaseous fuels. During the first half and the middle of the twentieth century, only a few works sporadically appeared that were dedicated to the torrefaction of biomass for energy. However, more information and fundamental data on heat treatments of lignocellulosic materials can be found from this period, mainly on high temperature drying, dry distillation, thermal degradation, pyrolysis, thermal stabilization, and preservation of wood.

5.1. Research Focused on Torrefaction

The development of modern works in the area of torrefaction can be divided into the pioneering French publications documented by *ARMINES Assoc pour Recherche et Dev des Methodes et Process Ind* [69] and Bourgois et al. [70,71], from 1981 to 1989, and the recent and extensive efforts of a large number of groups initiated by the work of scientists and engineers at the Eindhoven University of Technology and the Dutch Center for Energy (ECN) [72]. In the late 1980s, initial research implemented in France resulted in a specialized unit in France, where torrefaction was utilized to create a reducing agent for the metallurgical industry. The unit was built by the Pechiney enterprise and operated for a few years until it was dismantled for economic reasons. It must be mentioned and acknowledged that other scientific research was carried out during this period, in parallel with the French and Dutch works [73].

The torrefaction of biomass has been attracting a considerable amount of attention in the research community in the last few years [27,74–78]. Thus, the authors proceeded to the quantification of this interest. By examining all publications that mention biomass torrefaction for this study the authors sought to gather the current research. The aim of the analysis made in this study was to highlight further advances in the use of torrefaction. In this review, journals, conference proceedings, and book chapters were all considered to make this study as broad as possible. In the case of this study, the most significant databases were utilized in search of related papers. The databases used for this search are: Elsevier, Springer, MDPI, IEEE Xplore, Taylor & Francis, Wiley, Emerald Insight, Nature, and Inderscience Online. These databases were chosen as they comprise almost all the publications on this subject.

After compiling and categorizing all found publications, more than a few conclusions can be reached. The first finding is that 2304 publications were found in the above mentioned databases. The second finding is that the majority of the publications concerning the torrefaction of biomass have been published relatively recently, as can be seen in Figure 5. Also, by observing this figure, it is possible to deduce that the number of publications has been increasing almost exponentially and academic interest in this topic has been steadily growing. In Figure 6, the distribution of publication by database can be seen. By carefully observing Figure 6 it can be concluded that the majority of biomass torrefaction publications can be found in the Elsevier database.

5.2. Future Perspectives and Research Developments

The increasing interest of the industry in the use of fuels also causes an increase in the studies that involve this subject to improve the production of biomass while reducing the costs of this process [25].

As previously mentioned, torrefaction parameters affect the final properties of biomass, thus, studies are required that investigate such parameters to find the best set to obtain an ideal torrefied biomass sample [16,22].

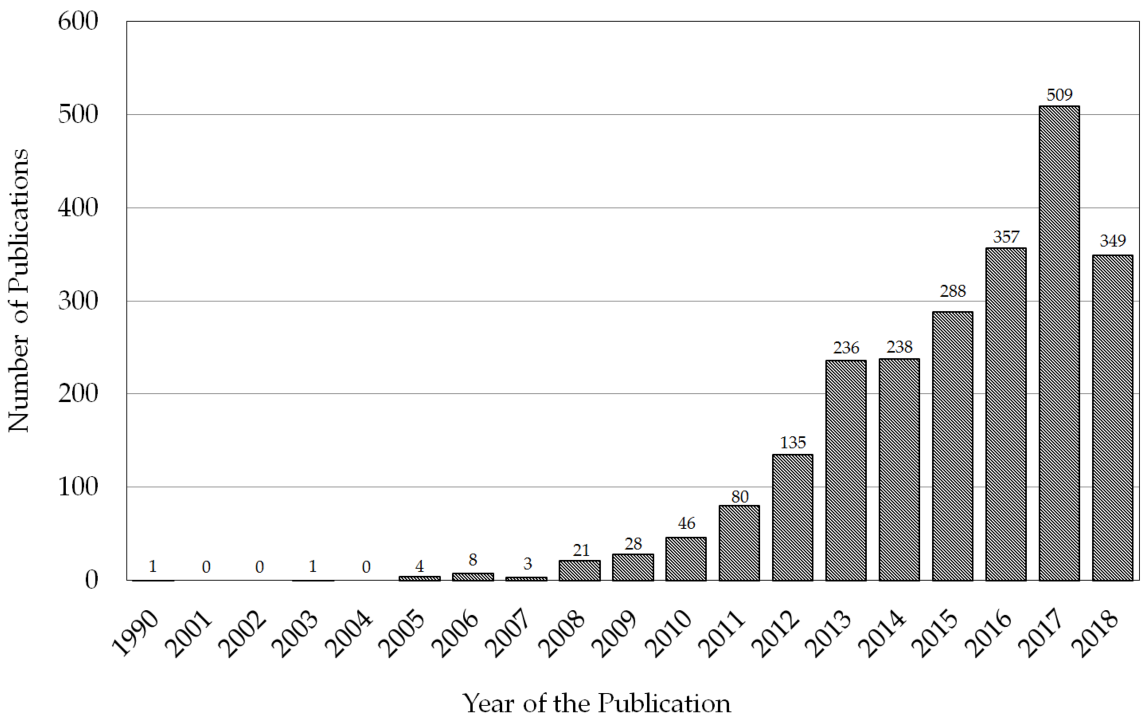

Figure 5. The year of publication of all the publications concerning the torrefaction of biomass.

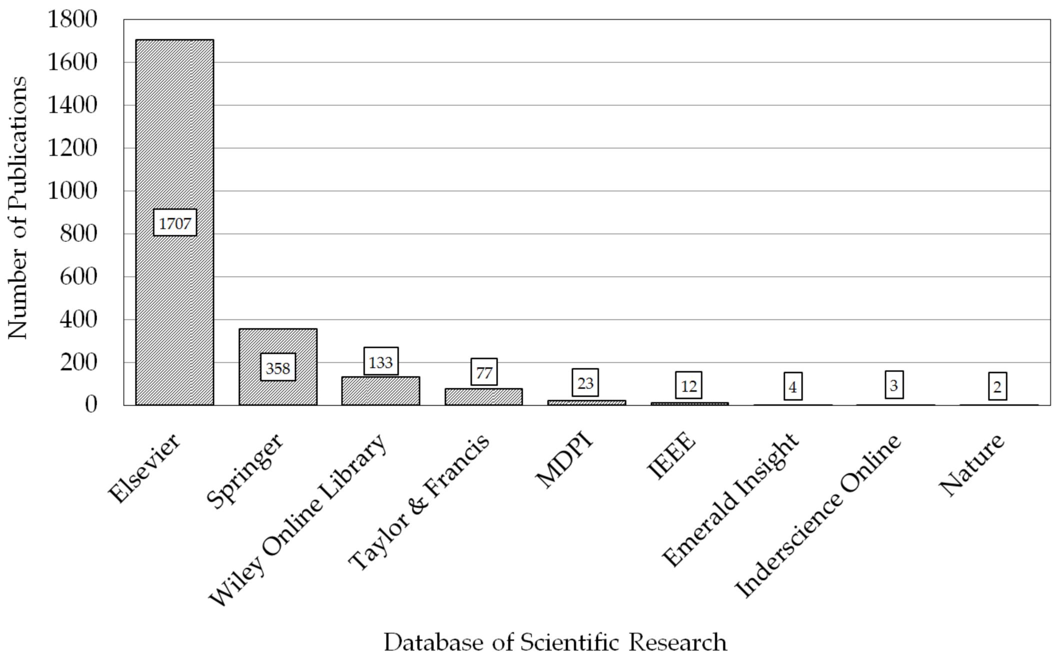

Figure 6. The number of biomass torrefaction publications per database.

To investigate the influence of temperature and residence time on the final biomass quality, Grigiante et al. analyzed the effect of different temperature pathways versus time to obtain mass yield rate values for samples of pine biomass. The results allowed the conclusion that, regardless of the route used, for the same temperature and time values, the TYR is the same. These parameters affected, to a large extent, the final results of the TYR, however, considering the low temperature range chosen, the temperature oscillation did not provoke oscillations in the final biomass energy parameters [79]. Chen et al. studied cellulose, lignin, and hemicellulose at a range of torrefaction temperatures based on the properties of their three-phase products, and a substantial difference in torrefaction characteristics was found due to their different molecular structures [75]. In [77], the characterization of biomass waste torrefaction under conventional and microwave heating was studied and the conclusions indicated that microwave torrefaction is more efficient for biomass upgrading and densification than conventional torrefaction.

Little attention has been directed to the definition of a numerical representation of the quality of biomass torrefaction. In addition to not having a complex database for biomass torrefaction, there is also an index that quantifies the torrefaction degree and shows the effect of the type of biomass used, as well as the effect of torrefaction parameters [80]. Almeida et al. noticed a linear relationship between mass loss and energy yield and carbon fixation of torrential biomass for a range of temperatures [81]. Li et al. observed a linear relationship between mass yield and energy yield, whereas Peng et al. used the mass loss as an indicator of the torrefaction state and developed a linear relationship between energy density and mass loss [54,82]. However, these parameters would have to be measured separate from the torrefaction process. Thus, Basu et al. attempted to develop a quantitative parameter to measure the degree of torrefaction by specifically targeting its goal for the energy industry. Three torrefaction regimes were then defined: Mild, medium, and severe, according to the temperatures used and the torrefaction rates obtained [80]. In [78], different kinetic, volatile release, and solid composition models were analyzed through numerical simulations and optimized different biomass.

Hence, torrefaction is a technique that exploits biomass characteristics to the maximum extent and it is important to consider efficient conversion techniques. With increasing knowledge about the torrefaction of plants, such as bamboo or sugar cane, it is necessary to make the most of the properties of these plants, since they have high growth rates, low ash formation, low alkaline index, and low heating rates. Therefore, Rousset et al. tested different properties of torrefied bamboo, comparing them with the properties of other solid fuels. The results allowed the conclusion that this type of biomass has much improved energy properties after its torrefaction [83]. The torrefaction of many different plant volatile organic compounds are starting to attract the attention of the research community. Poudel et al. conducted a comparative study of the torrefaction of empty fruit bunches and palm kernel shell performed in a horizontal tubular reactor at a temperature ranging from 150 to 600 °C [84]. They concluded that 290–320 °C is the required temperature range for optimum torrefaction of empty fruit bunches and 300–320 °C is the optimum range for palm kernel shell. In [85], the energy densification of sugarcane bagasse through torrefaction under minimized oxidative atmosphere was studied. The results indicated that torrefaction improved several fuel characteristics, making the sugarcane bagasse suitable for both domestic and industrial applications. Other possibilities of torrefaction have been applied and studied, such as for microalgae [86], Black Lilac (*Sambucus nigra* L.) [87], *Prosopis juliflora* [88], corncob [89], almond and walnut shells [90], bamboo sawdust [91], rice husk [92], and cotton stalk [93], among many others [94].

Brachi et al. have studied an innovative torrefaction process based on fluidized bed technology at various temperatures and with different residence times, using tomato peels as the raw material. This shows that it is possible to take advantage of low quality raw materials and, through torrefaction, improve them, thus, reducing the costs of obtaining raw material. The results of this study showed that it is possible to increase the energetic quality of the starting material by maintaining its TYR. This study also showed that this technology has numerous possibilities for its use in torrefaction when it comes to non-wood raw materials, allowing a uniform and consistent quality of the final torrefied products [95].

Álvarez et al. addressed the non-oxidative torrefaction of biomass to enhance its fuel properties in which both the hydrophobicity and the fixed carbon were increased [76]. Chen et al. researched the effect of torrefaction pretreatment on the pyrolysis of rubber wood sawdust through pyrolysis-gas chromatography/mass spectrometry and concluded that the contents of oxy-compounds, such as acids and aldehydes, decreased with rising torrefaction temperature [74]. Finally, in [86], the effects of torrefaction on physical properties, chemical composition, and reactivity of microalgae were studied. For the development of an ideal torrefaction protocol, Rodrigues et al. analyzed the effects of torrefaction undergoing normal conditions of temperature (265 °C) and residence time (15 min) in an N atmosphere and during a total 1 h 45 min heating period on a set of sixteen woody biomasses provenient from poplar short rotation coppice (SRC) and other Portuguese roundwoods [53].

5.3. The Current State of the Built Production Units

Of the more than 60 announced torrefaction initiatives and the 15 large-scale units scheduled to start by 2011, very few were built and hardly ever achieved a steady total industrial production and commercial status. The assumptions and expectations for the start-up were initially very high. Most equipment suppliers tend to overstate their capabilities and underestimate the time and effort required. Technological entrepreneurs with limited biomass experience have also encountered difficulties in the face of simple challenges, such as food, transport, storage, and quality of raw materials. Another issue is the relatively high total costs. "Drying and re-drying a little more", seems very simple, and attracted a huge group of serious entrepreneurs, but also the so-called "fortune hunters". However, torrefaction is a more complex process than initially anticipated.

Torrefaction must be conducted intelligently, with controlled costs, and is entirely directed towards the progress and success of the marketing. There are currently a number of challenges in systems and processes that require careful research and development (R&D) and intelligent solutions, such as: Processing and control of the atmosphere; gas production for inertization; heat transfer; control and moderation of exothermic reactions; cooling of products; behavior of the torrefaction gases, their deposition, and use; integration of systems and processes; energy optimization and exergetics; densification; and the optimization of the entire process supply chain. Perhaps, the most important part is the diagnosis and control of the process. Due to the close relationship between temperature and residence time with the product quality and standardization, careful control of these process variables is critical.

The material produced should be completely homogeneous, with respect to the degree of torrefaction, and preferably dark brown (not over-torrefied), to allow sufficient yield and to facilitate densification. There are few initiatives that are paving the way for the torrefaction industry. There are currently five industrial torrefaction units constructed and functioning in Europe [33] and at least eight units of torrefaction are planned and ready to begin functioning in the near future. These torrefaction industrial units are presented in Table 3.

Table 3. Torrefaction industrial units planned to begin operation in the near future.

Name of the Facility	Country	Capacity of Production in Tons Per Year
Biolake	The Netherlands	9000
Thermya	Spain	20,000
ECN/Andritz	The Netherlands	8–16,000
Fox Coal	The Netherlands	35,000
EBES/Andritz	Austria	8000
Bio Endev	Sweden	16,000
Rotawave	USA	100,000
Advanced Fuel Solutions	Portugal	96,000

6. Conclusions

The potential of biomass as a replacement to fossil fuels leads to a number of issues, such as the increase in their price and environmental consequences due to their excessive harvesting and plantation. This leads to an increase of studies that address this topic to improve the production of biomass while reducing its cost. The torrefaction of biomass has proved to be an ideal process for improving the biomass characteristics as this energy source has proved to be a good alternative to the use of fossil fuels.

Nowadays, the torrefaction of biomass is still an experimental technology, but due to the characteristics of the resulting products, it seems to be a promising technology that generates the curiosity and interest of the sector's investors. From this perspective, the potential development of biomass thermal conversion technologies, such as torrefaction and/or carbonization, is considered promising regarding the utilization of new forms of biomass, namely, the less environmentally friendly, more abundant, and faster growing forms, as is the case of shrub plants.

The main goal of this article was to present fresh information regarding the conventional torrefaction process, as well as to analyze the literature and study the innovative techniques that have been in development for the improvement of torrefied biomass qualities. The results show that the publications regarding this topic have been strongly increasing, which suggests a strong academic and industrial interest for this subject in the last few years. Several of these studies were analyzed and the future perspectives and research developments were consequently addressed.

However, some effects are less positive, since there is a risk that the widespread consumption of biomass could affect various ecosystems by creating negative impacts on the quality of water and soil and affecting food chains. Another potential consequence of biomass production is its overproduction, which leads to deforestation and a consequent decrease in biodiversity. These less positive aspects were also addressed.

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