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Review

Biochar: From Laboratory to Industry Scale—An Overview of Scientific and Industrial Advances, Opportunities in the Brazilian Context, and Contributions to Sustainable Development

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Abstract: Waste treatment and valorization have become crucial for sustainable development towards a circular economy. As an alternative, biochar production is a promising process to convert wastes into a valuable product that presents several potential applications to cope with environmental problems. Biochar in recent years has been the subject of many studies, which have leveraged the number of patents and the industrial interest in this process. Against this background, this overview aimed: (i) to identify the advances in biochar research; (ii) to assess the number of patents on biochar over the years; (iii) to look at the industrial production of biochar worldwide; (iv) to detect the potential for biochar production in Brazil regarding waste biomass availability; and (v) to discuss the potential of biochar in contributing to reach some Sustainable Development Goals (SDGs). The holistic analysis presented here suggests that progress has been made in research, patent development, and industrial implementation of biochar, and that its potential role in achieving certain SDGs is noteworthy. Therefore, this overview can be useful in guiding future research about biochar to improve the knowledge of the different branches in this field.

Keywords: waste valorization; pyrolysis; hydrothermal carbonization; gasification; biochar industry; sustainable development goals

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1. Introduction

The search for waste treatment and recovery solutions to mitigate environmental impacts has become crucial to achieving the United Nations' Sustainable Development Goals (SDGs) and thus implementing a circular economy. In this context, biochar has emerged as a promising alternative since its characteristics make it attractive for the treatment and recovery of waste [1]. Biochar is a carbon-rich solid obtained from the decomposition of organic materials through thermochemical processes such as pyrolysis, hydrothermal carbonization (HTC), gasification, and torrefaction [2,3]. Biochar possesses physicochemical properties, such as a large specific surface area, high pore volume, functional groups on the surface, and high carbon content, which make it suitable for various applications. These include biochar utilization as an adsorbent, a precursor for catalysts, a soil amendment agent, and an additive for anaerobic digestion/composting [1,3]. In this way, the broad applicability potential of biochar and the waste management that the technology provides circumvent the production–use–disposal approach (linear economic model), making possible the reincorporation of wastes into the economic chain and thus promoting a circular economy.

Biochar research has exponentially increased in the past decade [4]. Studies proposing different wastes (e.g., agricultural and woody wastes, sewage sludge, digestate, plastic, algae, coal, tire wastes, and livestock manures) as feedstocks for biochar production are abundant [5–7]. Similarly, there is a growing number of articles reporting process (e.g., pyrolysis, HTC, gasification, and torrefaction) optimization, aiming to provide suitable conditions of temperature, reaction time, and feedstock load [8–11]. Thus, the potential of biochar has boosted research on its economic and environmental feasibility given the life cycle and techno-economic assessments reported [12–16].

In response to research developments, the number of patents about biochar has increased as well. This trend indicates that biochar is a promising marketable product, which has aroused industry interest in scaling up biochar production processes. In Europe, for example, the biochar market has grown strongly. Production was about 33,500 tons at the end of 2022, but the production capacity was 53,000 tons in the same period [17]. Some reports indicate that the global biochar market will continue to grow this decade, suggesting consolidation of the biochar industry [18–20]. Furthermore, in addition to enabling economic gains, biochar production fits with sustainable development proposals. It has been suggested that biochar has the potential to contribute to reaching the UN Sustainable Development Goals (SDGs) due to its possible application to mitigate environmental problems [21]. For example, hydrochar (biochar) can be used as an adsorbent for water remediation by removing pollutants such as emerging contaminants (e.g., disrupting compounds, antibiotics, and pesticides), heavy metals, and dyes [10], contributing to the achievement of SDG 6 (Clean water and sanitation) [22].

According to the scenario depicted, studies that approach biochar production from a broad perspective are important for the advancement and consolidation of this technology as part of the global environmental agenda. Thus, to understand the state of the art of this topic, it is necessary to look first at the academic field, since basic research continually suggests possible alternatives to biochar production. Subsequently, it is important to look at the industry to identify the consolidated processes in the market. Finally, it is essential to evaluate the effects of this practice from an economic, social, and environmental perspective. Therefore, the aims of this review were: (i) to identify the advances in biochar research; (ii) to assess the number of patents on biochar over the years; (iii) to look at the scale of industrial production of biochar worldwide; (iv) to detect the potential for biochar production in Brazil regarding waste biomass availability; and (v) to discuss the potential of biochar in contributing to reach some of the SDGs. To the best of the authors' knowledge, the originality of this overview is to provide a holistic outlook on the biochar field from laboratory to industrial scale, in addition to suggesting Brazil's potential in this area and indicating the possible influence of biochar production in reaching sustainable development.

2. Methodology

The Scopus database was used to analyze the evolution of biochar research from 2014 to 2023 regarding the number of publications, the countries with the most publications, and the subject area. The processes addressed were pyrolysis, HTC, gasification, and torrefaction, and only research articles were considered. The search was only within article titles, abstracts, and keywords, and used the following terms: (i) "biochar AND pyrolysis" for pyrolysis, (ii) "(biochar OR hydrochar) AND 'hydrothermal carbonization'" for HTC, (iii) "biochar AND gasification" for gasification, and (iv) "biochar AND torrefaction" for torrefaction. The term "hydrochar" was included in the search about the HTC process because it is the name given to the biochar obtained through this method.

To assess the number of patents on biochar over the years, the PATENTSCOPE database of the World Intellectual Property Organization (WIPO) was used. Initially, a general search from 2015 to 2023 was conducted using the term "biochar OR bio-char". Subsequently, the search was refined using the term "(biochar production) OR (bio-char production)". The International Patent Classification (IPC) search filter was used to facilitate the search for patent documents found in each keyword combination. The most recent patents published in the two classification codes with the highest number of registrations were evaluated.

The worldwide biochar-producing companies were found from an online search considering the biochar market. The initial list of companies was subjected to a refinement process, considering those that had the data of interest for this study: year in which operations began, annual production capacity (ton/year), production technique, and raw material used. Companies that did not have this data and those with annual production of less than 200 tons per year were not considered. According to the European Biochar Industry Consortium (EBI), the companies are classified as follows: medium (200–499 tons/year), large (500–1999 tons/year), very large (2000–4999 tons/year), and industrial (≥5000 tons/year) biochar production capacity [17].

To analyze Brazil's biochar production potential regarding waste biomass availability, a search was carried out to quantify the amount of potential biomass wastes that could be available for biochar production in the country. For this purpose, the following residues were considered: (i) crop wastes from sugarcane, soy, corn, cassava, cotton, orange, beans, rice, wheat, and coffee production; (ii) livestock wastes, which included manure from cattle, swine, poultry, buffalo, and goats and sheep; (iii) forestry wastes from roundwood production; (iv) sewage sludge from municipal wastewater treatment plants (WWTP); and (v) municipal solid wastes (MSWs).

Finally, to analyze the relationship between the use of biochar and the SDGs, this study considered goals 6 (Clean water and sanitation), 7 (Affordable and clean energy), and 13 (Climate action), for which biochar production and application might have a direct impact. The choice of these SDGs was based on the relationship between biochar and water/wastewater management, access to energy, climate change mitigation, and biodiversity promotion.

3. Outlook on Biochar Research

Biochar is a carbon-rich solid material resulting from the thermochemical conversion of biomass wastes [23]. Its production is emerging as a promising technology for waste treatment and valorization [1]. The main processes to produce biochar are pyrolysis (fast and slow), gasification, HTC, and torrefaction. Table 1 presents some examples of these biochar production processes using different biomass wastes and the respective biochar yields and characteristics (proximate and ultimate analysis, higher heating value (HHV), and specific surface area (S_{BET})). Accordingly, biochar characteristics depend on the production method and its conditions (e.g., temperature) and biomass waste (Table 1). Furthermore, biochar can still be subjected to physical, chemical, or biological modifications to improve its characteristics [24–26].

Table 1. Examples of biochar production processes using different biomass wastes and the respective biochar yields and characteristics (proximate and ultimate analysis, higher heating value (HHV), and specific surface area (S_{BET})).

Method of Production	Waste	Temperature (°C)	Biochar Yield (wt%)	Biochar Characteristics								Refs.
				Ultimate Analysis (wt%, db [a])			Proximate Analysis (wt%, db [a])			HHV (MJ kg^{-1})	S_{BET} (m^2 g^{-1})	
				C	O	H	Ash	VM [b]	FC [c]			
Fast pyrolysis	Rice husks	550	39	44.7	7.7	1.8	45	14.2	40.8	17.7	117	[27]
	Used tires	500	40	85.1	-	0.53	11.7	9.1	80.2	29.7	-	[28]
	Wheat straw	500	26	56.0	-	2.3	32	16	-	-	-	[29]
	Pig manure	450	25	83	<5	<10	-	-	-	-	-	[30]
	Wood chips	450	18.5	82	5	<10	-	-	-	-	-	[30]

Table 1. *Cont.*

Method of Production	Waste	Temperature (°C)	Biochar Yield (wt%)	Biochar Characteristics								Refs.
				Ultimate Analysis (wt%, db [a])			Proximate Analysis (wt%, db [a])			HHV (MJ kg^{-1})	S_{BET} (m^2 g^{-1})	
				C	O	H	Ash	VM [b]	FC [c]			
Slow pyrolysis	Rice husks	300	38	46.1	23.3	3.8	22.7	43.1	30.6	17.6	-	[31]
	Coffee husks	350	40	69.9	22.5	3.6	9.8	24.1	66.1	26.7	-	[32]
	Wheat straw	300	95	50.3	-	6.2	8	76.3	23.7	-	-	[33]
	Pine wood	300	90	54.1	-	5.9	0.3	78.0	22.0	-	-	[33]
	Cow manure	300	81	30	-	-	-	-	-	-	97	[34]
Hydrothermal carbonization (HTC)	Pine wood	220	56.5	63.5	31.1	5.3	0.02	68.7	31.2	24.1	8.2	[35]
	Corn silage	250	52	62.8	17.1	5.5	12.3	-	-	26.5	4.9	[36]
	MSW	220	54.8	66.6	16.8	7.0	5.8	69.5	24.7	29.9	-	[37]
	Pine sawdust and sewage sludge	250	64	55.8	16.2	4.3	18.4	59.3	22.3	20.3	22.7	[38]
Gasification	Elephant grass	300	14.3	-	-	-	-	-	-	-	475.1	[39]
	Grape pomace	1200	15	53	41	3.9	42.3	12.8	44.8	-	76.1	[40]
	Miscanthus plant	600	25.5	92.9	3.8	2.4	12.2	15.3	72.5	-	403.5	[41]
		800	22.6	92.5	5.2	1.6	12.3	8.8	78.9	-	629.3	
		1000	20.6	91.7	5.4	2.2	13	8	79	-	981.7	
Torrefaction	Wood pellets	250	89.1	-	-	-	1.7	72.2	26.1	19	-	[42]
	Rice husk	250	52	57.2	22.9	4.5	14.3	42.4	43.3	22.6	-	[11]
	Coconut husk	250	60	58.6	26.9	4.2	9.6	40.4	50	22.4	-	
	Cassava rhizome	250	50	58.7	25.8	5	9	40.4	50.5	23.5	-	
	Corncob	250	40	62.2	27.1	5.1	4	39	57	24.9	-	
	Microalgae residue	250	71.6	36.5	49.5	6.1	23.8	61.8	12.5	12.6	-	[43]

[a] db: dry basis; [b] VM: volatile matter; [c] FC: fixed carbon.

3.1. Pyrolysis

Pyrolysis is a thermochemical process for converting biomass into high-value products, such as biochar, bio-oil, and syngas, in the absence of oxygen over a temperature range of 300 to 900 °C [44]. In pyrolysis, the liquid product is commonly known as bio-oil, which can be stored and refined for energy production, while the volatile fraction contains a mixture of non-condensable gases such as CO, CO_2, H_2, CH_4, and heavier hydrocarbons, which are generally referred to as pyrolysis gas or syngas [45]. The solid product of this process (biochar) has a high carbon content and can be used, for example, as an energy source or for soil improvement [46]. In general, pyrolysis can be subdivided into slow pyrolysis (low heating rate and long residence time) and fast pyrolysis (high heating rate and short residence time), based on the temperature, heating rate, pressure, and residence time used [47].

The purpose of slow pyrolysis, which takes place between 400 and 600 °C, is to maximize the yield of biochar [48]. This process is carried out at atmospheric pressure and has a long residence time (>1 h) and slow heating rates (5 to 7 $°C \cdot min^{-1}$). Different reactors can be used to produce biochar, such as agitated drums, rotary sand kilns, wagon reactors, and blade pyrolysis kilns [3]. Fast pyrolysis, however, has the advantage of increasing the yield of bio-oil (up to 75%) from biomass, with a heating rate generally higher than 200 $°C \cdot min^{-1}$ and a residence time of less than 10 s [49]. For fast pyrolysis, different reactors can be used, such as bubbling fluidized beds, circulating beds, rotating cone reactors, and ablative reactors [50].

Figure 1A depicts a considerably growing trend of publications about biochar from pyrolysis between 2014 and 2023. In 2014, the number of research articles was 284, while in 2023 it had grown to 1734. Such a trend emphasizes the researchers' interest in pyrolysis to convert biomass wastes into biochar over the years. According to Figure 1B, the country with the highest number of publications from 2014 to 2023 is China (4191), which is followed by the United States (979) and India (615). It is interesting to note that 28.8% of the research articles are in the area of Environmental Science (Figure 1C). This evidence thus demonstrates the potential of biochar production through pyrolysis in addressing environmental issues. For instance, the examples presented in Table 1 for pyrolysis (fast and slow) show that all biochar had a high value of fixed carbon (FC), which is beneficial when using biochar as a solid biofuel. Moreover, the specific surface area of biochar obtained from pyrolysis processes can suggest the potential of this material as an adsorbent for pollutant removal.

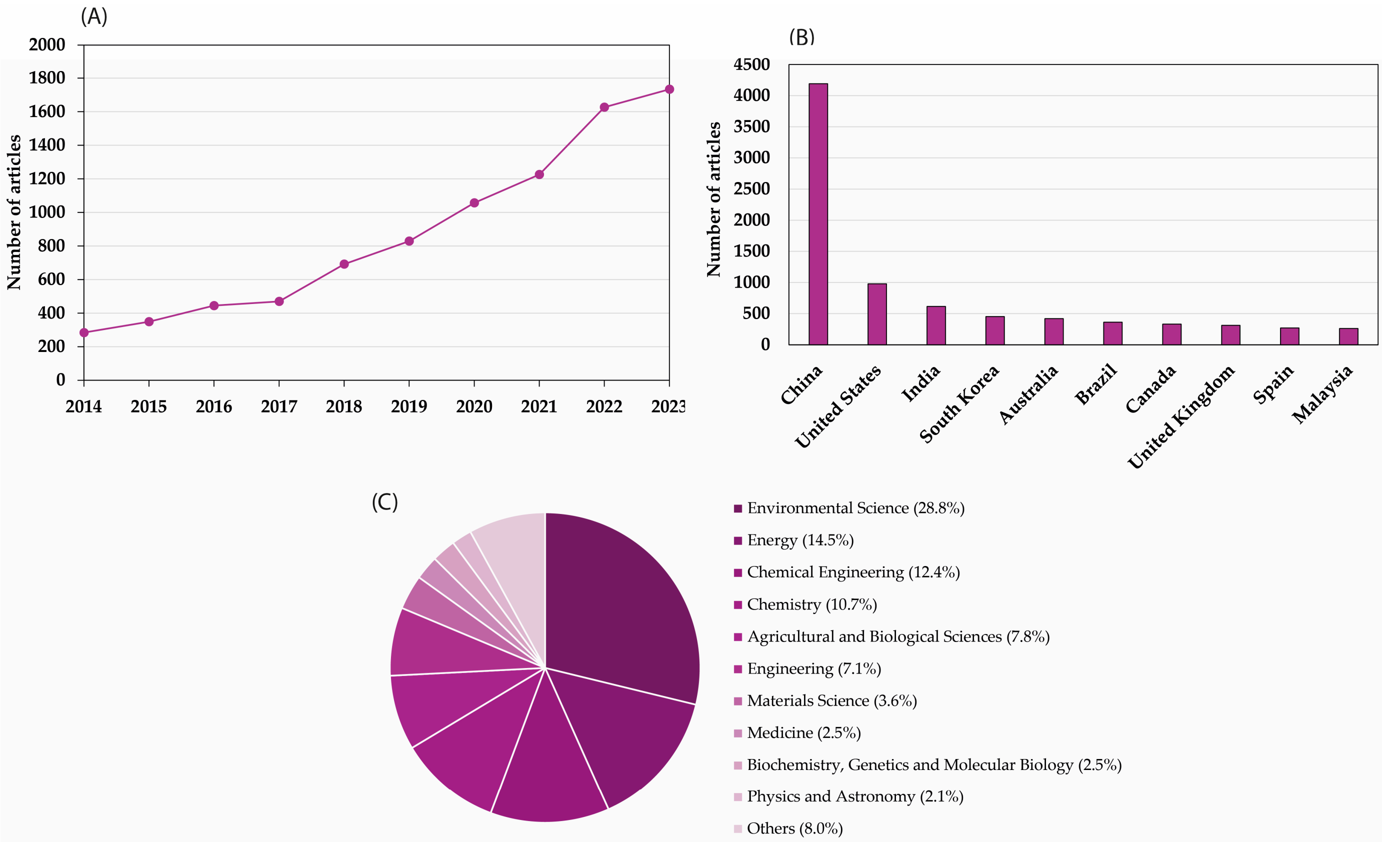

Figure 1. Number of publications of research articles (**A**), the 10 countries with the most publications of research articles (**B**), and the main subject areas of the research articles found (**C**) on biochar from pyrolysis from 2014 to 2023.

3.2. *Hydrothermal Carbonization (HTC)*

HTC is a suitable method for treating biomass with high moisture content [51]. This thermochemical process consists of subjecting the biomass to low temperatures (between 180 and 250 °C) and autogenous pressure in the presence of water [10]. Thus, the product of interest is named hydrochar, a type of biochar with different properties from those obtained by pyrolysis and gasification, which can have a yield of between 40 and 70% by weight [52]. The yield and quality of hydrochar depend on the composition of the biomass: lignocellulosic waste generates more mass and energy, while waste rich in low molecular weight carbohydrates, such as corn silage, generates a hydrochar more like lignite and peat [53]. The effluent produced during HTC can be reused, reducing the environmental impact, and increasing the energy efficiency of the process [3]. Table 1 presents the HTC temperature and biochar yield of biochar from different wastes. It is possible to note the great difference in HTC temperatures compared with those used in pyrolysis and gasification processes.

The interest in HTC has increased in the past 10 years, as reported in Figure 2A. The number of research articles published in 2014 was 51, and it increased steadily over time, reaching 376 in 2023, representing an increase of more than 700% in research articles about hydrochar (biochar) and HTC in that period. Similarly to pyrolysis, China (796) leads the publication scenario and is followed by the United States (186). The third position, however, is occupied by Germany (180). In Figure 2C, it is possible to note that, like pyrolysis, most of the research articles (43.2%) are within the Environmental Science and Energy areas. In Table 1, for example, all hydrochars from different wastes presented HHVs between 20 and 30 MJ·kg^{-1}, which are in the range of or even higher than those of coal [54]. This indicates the energetic potential of hydrochar.

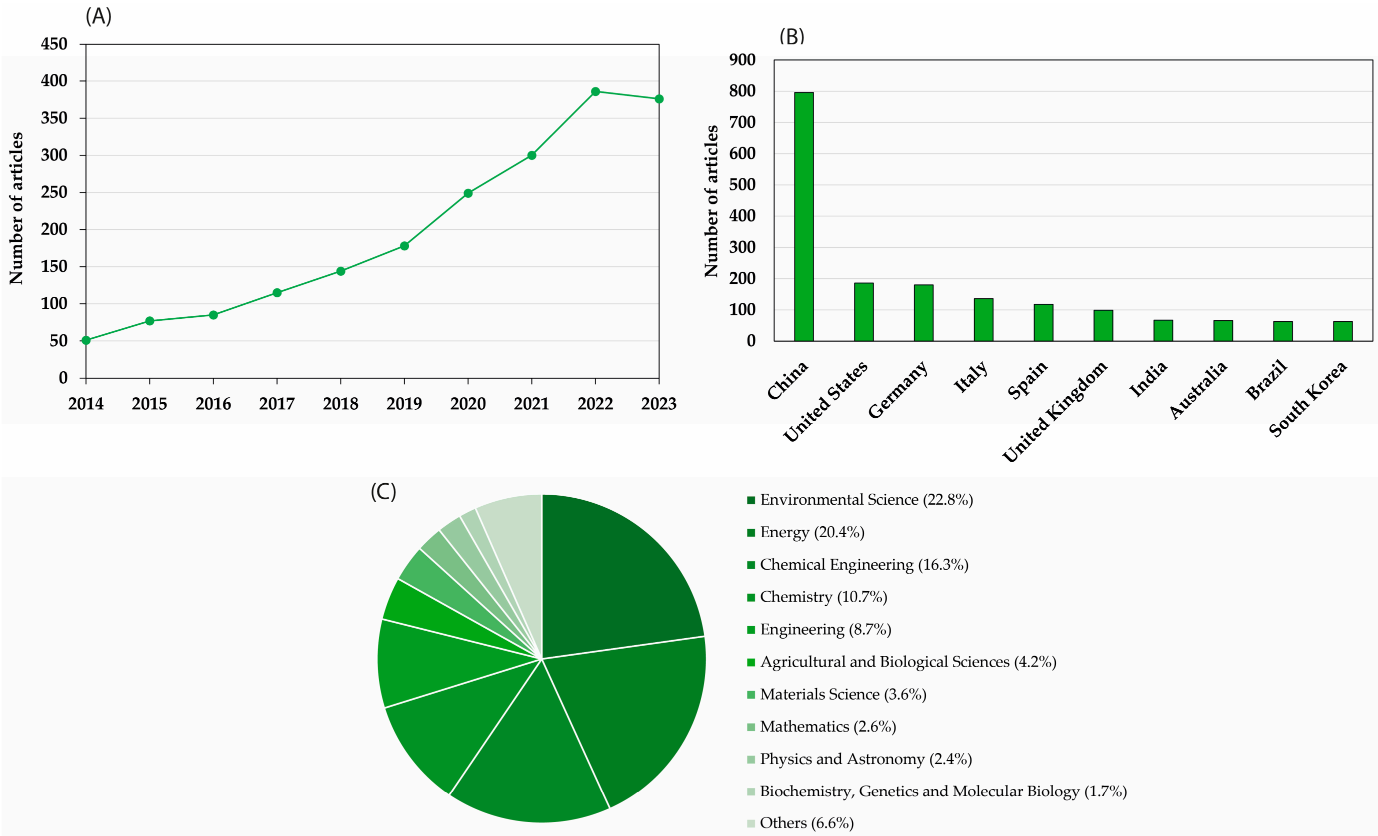

Figure 2. Number of publications of research articles (**A**), the 10 countries with the most publications of research articles (**B**), and the main subject areas of the research articles found (**C**) on biochar from hydrothermal carbonization (HTC) from 2014 to 2023.

3.3. Gasification

Gasification is a thermochemical process that converts a carbon source, usually with low moisture, into a gaseous mixture (syngas) in the presence of an oxidizing agent (oxygen, air, water vapor, or combinations thereof) at high temperatures (>700 °C) [49]. The process generally yields lower biochar than pyrolysis [55]. For instance, as presented in Table 1, the biochar yield from grape pomace gasified at 1200 °C was only 15%. Biochar is not the targeted product of gasification, which is performed to obtain syngas. In fact, biochar can be considered a byproduct of gasification [56].

However, the interest in gasification in the context of biochar production is depicted in Figure 3A. The number of research articles reached 146 in 2023 from 29 in 2014. Regarding publication by country (Figure 3B), China (290), the United States (122), and Italy (68) are the three countries with the highest numbers of publications. The predominant subject area of the research articles is Energy and Environmental Science, encompassing 44.6% of all documents (Figure 3C). In Table 1, it is possible to verify the high FC contents (44% to 79%) and remarkable surface areas (76 to 971 $m^2 \cdot g^{-1}$) of the biochars obtained through gasification. These characteristics suggest, therefore, that these biochars could be utilized for energy generation or adsorption purposes.

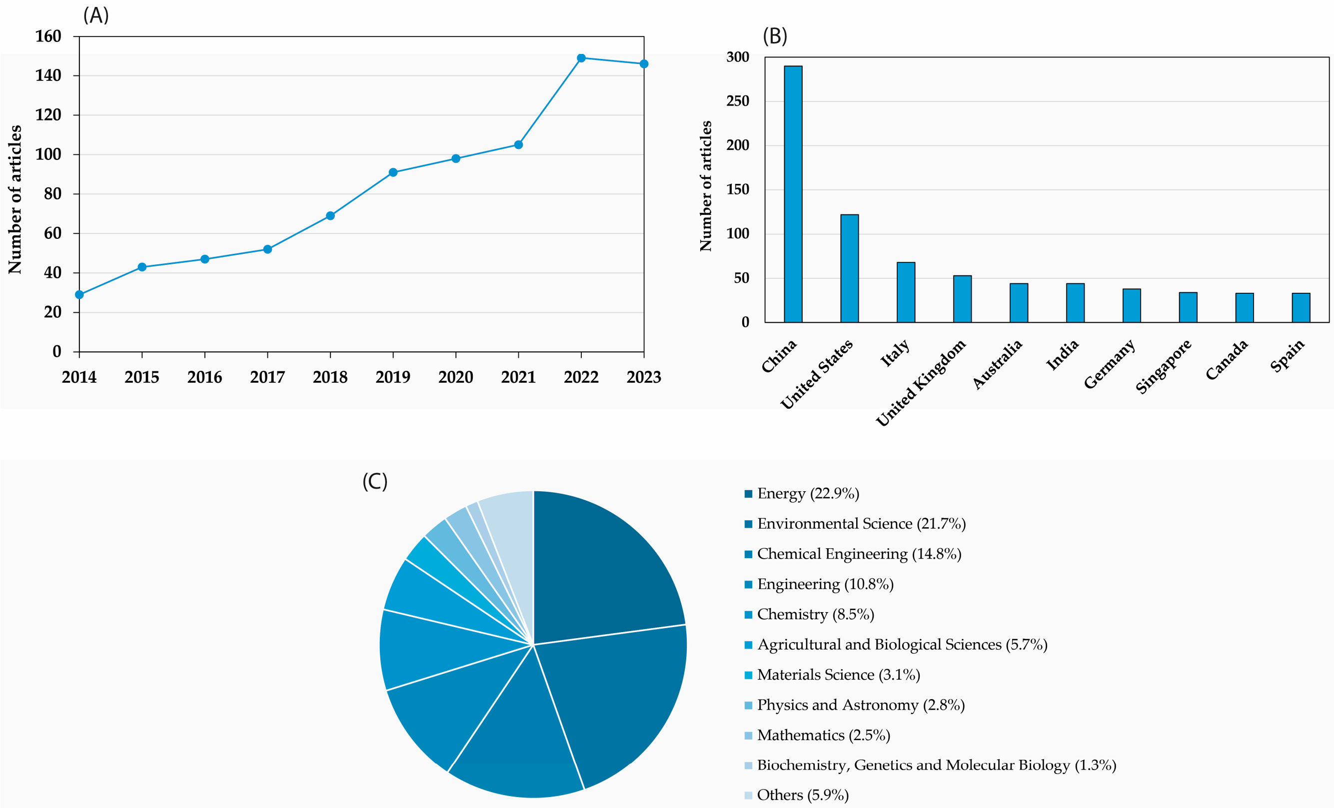

Figure 3. Number of publications of research articles (**A**), the 10 countries with the most publications of research articles (**B**), and the main subject areas of the research articles found (**C**) on biochar from gasification from 2014 to 2023.

3.4. Torrefaction

In torrefaction, the biomass is heated at temperatures of 200 to 300 °C in an inert atmosphere. This process has also been called mild pyrolysis, and it aims to upgrade the fuel potential of solid waste biomasses. Thus, torrefaction could improve the energy density of waste biomasses by increasing the HHV given the reduction in the moisture content and the O/C and H/C atomic ratios [11,57].

Figure 4A indicates an increase in torrefaction research in the context of biochar, although it is more modest than that reported for the other thermochemical processes discussed above. China (102), according to Figure 4B, still leads the number of documents published from 2014 to 2023, followed by Taiwan (78) and the United States (40), which appeared in the third position. Moreover, it is worth noting that the main area of publication is Energy (27.1%), being different from HTC and gasification, whose Environmental Science and Energy domains had almost the same percentage. From an energetic perspective, therefore, torrefaction can be a suitable option to produce biochars with good HHVs, as exemplified in Table 1.

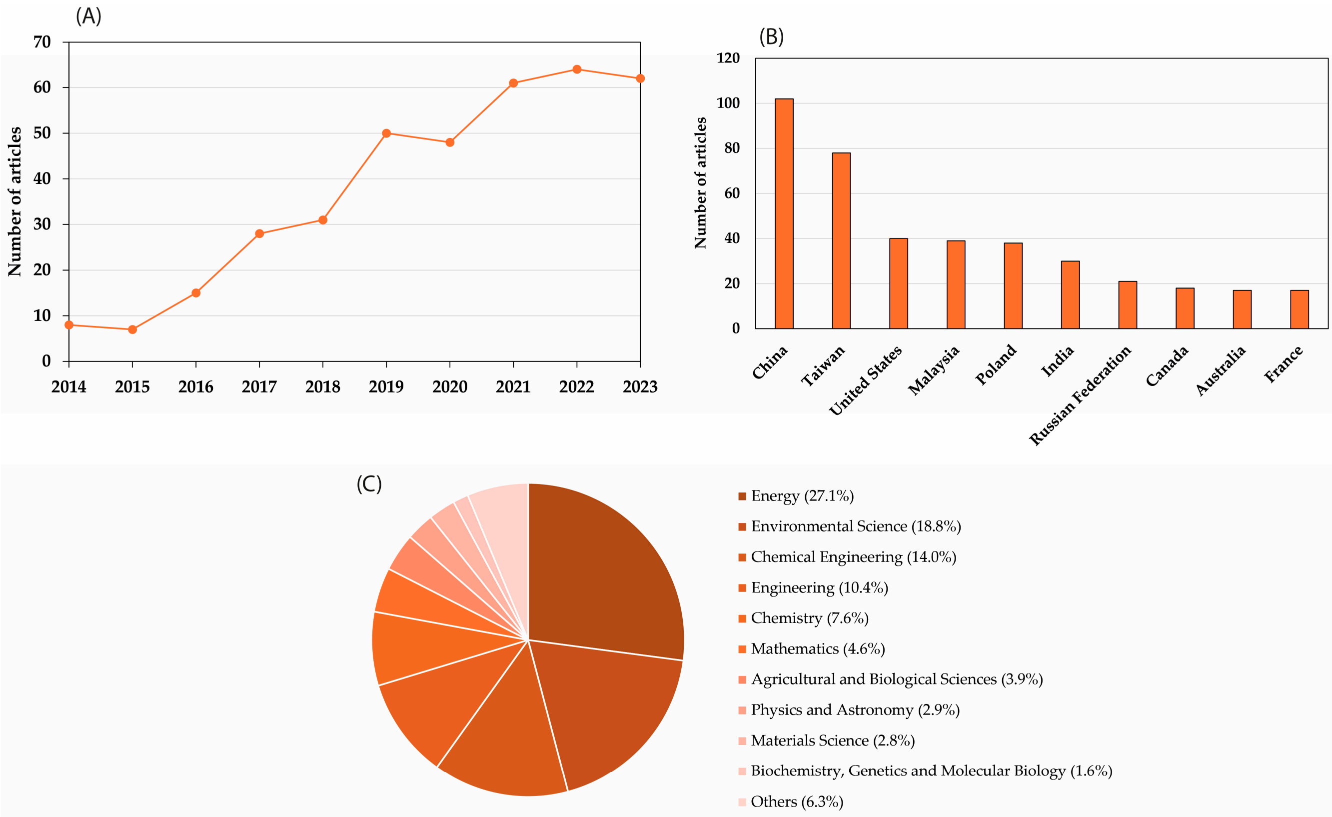

Figure 4. Number of research articles published (**A**), the 10 countries with the most publications of research articles (**B**), and the main subject areas of the research articles found (**C**) on biochar from torrefaction from 2014 to 2023.

4. Environmental Applications of Biochar

4.1. Waste Management

Proper waste management is a fundamental key in the search for sustainable environmental practices [58]. As the world's population grows and human activities generate an increasing amount of waste, the importance of effective strategies to deal with this challenge becomes evident [59]. In this context, a promising strategy to address the appropriate management of different types of waste could be biochar production.

The generation of sewage sludge, for instance, has been expanding worldwide due to the increased amount of waste to be discarded by WWTP [60]. Sewage sludge could thus be used to produce biochar. The organic content of sewage sludge biochar and its specific properties make it a good adsorbent for removing contaminants from wastewater [61,62]. Wastes from agriculture, forests, urban centers, and industries have also been studied to produce biochar [28,31,37,38]. For example, a study that used biochar from industrial and agricultural waste to enhance phosphorus concentration in a rice field demonstrated that the group fertilized with biochar showed higher phosphorus adsorption compared to the control group, thereby improving soil microbiology [63]. Another type of waste that has been increasing over the years because of rapid urbanization and population growth is MSWs [64]. To develop strategies to reduce the volume of these wastes, the pyrolysis process is considered a preferential approach for converting these wastes into biochar. It significantly reduces the volume of urban solid waste by up to 90%, establishing a more sustainable waste management regime [65].

In light of the above, biochar production could be a promising strategy for waste management and recovery. The transformation of organic waste into biochar not only reduces the environmental burden associated with the improper disposal of these materials but also contributes to mitigating greenhouse gas emissions and promoting environmental sustainability [66]. Furthermore, the strategic use of biochar in soil improves its physical and chemical properties and provides substantial benefits to agriculture by increasing the availability of nutrients and water for plants [67].

4.2. Adsorption of Pollutants

Biochar, given its physicochemical characteristics, emerges as a promising alternative for removing pollutants from soil and water, providing a suitable niche for the adsorption of a variety of organic and inorganic pollutants [68]. In the context of soil, biochar has demonstrated effectiveness in removing organic contaminants such as hydrocarbons and pesticides [3]. The possible adsorption mechanism involves several types of interactions, such as electrostatic attraction, ion exchange, physical adsorption, surface complexation, and/or precipitation [69]. It was demonstrated that biochar possesses several benefits for the soil, including the capacity to elevate the pH value and organic carbon content of the soil, enhance the soil's water retention capacity, reduce the number of contaminants, enhance crop yields, and inhibit the absorption and accumulation of pollutants by plant roots [70,71]. In aquatic systems, biochar is capable of adsorbing heavy metals, excess nutrients, dyes, and emerging contaminants (e.g., pharmaceuticals and pesticides) [10,72]. The physicochemical interactions between biochar and the pollutants present in the water form stable complexes, thereby reducing the concentration of pollutants in the media [69]. However, it is crucial to consider an appropriate biochar type and application conditions to optimize the desired results [3]. Thus, biochar stands out as a promising solution for promoting soil and water quality by adsorbing pollutants.

4.3. Energy Production

An overexploitation of fossil fuel-based energy resources represents a serious threat to the environment and society [73]. The burning of fossil fuels produces greenhouse gases and various toxic pollutants responsible for global warming, causing adverse effects on human health [74]. To reduce the use of fossil fuels for energy production, biomass can be used as a fuel source [75]. However, raw biomass is unattractive as fuel due to its high moisture content, which reduces overall combustion efficiency, while its low volumetric density results in higher transportation costs per unit of energy [76]. To convert raw biomass into products with enhanced fuel properties, such as biochar, thermochemical processes are necessary. Table 1 presents the HHV of different biochars.

As an example of energy production in the context of biochar, one can look at pyrolysis process. In addition to biochar, pyrolysis can also produce bio-oil and a gaseous fraction. Bio-oil consists of water, alcohols, phenolic compounds, aliphatic and aromatic hydrocarbons, and nitrogen compounds (pyrazine, pyridine, and amines), which can be used in boilers to generate heat [77]. The gaseous fraction, known as syngas, consists of CO, CO_2, H_2, CH_4, and other low molecular weight gases that can be used in gas engines after processing [78]. It is important to note that the fraction and properties of these three products (biochar, bio-oil, and syngas) strongly depend on pyrolysis conditions, such as temperature, residence time, and heating rate [79]. However, biochar, bio-oil, and syngas exhibit significant energy potential, standing out as biofuel options to mitigate the environmental impacts associated with fossil fuels [80,81]. This demonstrates that biochar production from pyrolysis for energy purposes should not be limited to the solid product (biochar) alone, but should also consider the liquid (bio-oil) and gaseous (syngas) outputs.

4.4. Carbon Sequestration

Biochar has gained increasing attention due to its possible advantages in carbon sequestration and mitigation of climate change, as it has a carbon content resistant to decomposition [82–84]. Biochar has a high content of aromatic carbon, which is the basis of its carbon sequestration capacity [85]. Thus, storing biochar in soils through agricultural management can also facilitate carbon sequestration [86]. Therefore, converting biomass wastes into biochar and storing the produced biochar in soils promotes carbon sequestration.

For instance, a national-level LCA was conducted to evaluate the carbon sequestration potential of biochar produced from various crop residues. The results demonstrated that the conversion of 1 ton of crop residues into biochar could result in the sequestration of more than 920 kg of CO_2e (CO_2-equivalent). The authors also indicated that the estimated annual carbon sequestration potential in China based on crop residue availability statistics for 2014 was as high as 0.50 Pg CO_2e (1 Pg = 1×10^9 tons) [87].

5. Patents Development

Patent databases represent an attractive and dependable resource for gauging the technological advancement and innovation that companies and universities have developed over the years. Thus, a search using the term "biochar OR bio-char" on the PATENTSCOPE database returned 11,654 patent documents. China (54.16%) and the United States (16.83%) are the countries investing the most in biochar, collectively accounting for almost 71% of the total intellectual property (Figure 5A). These results are in line with what was discussed in Section 3, as both China and the United States are the leading countries in terms of publishing research related to biochar.

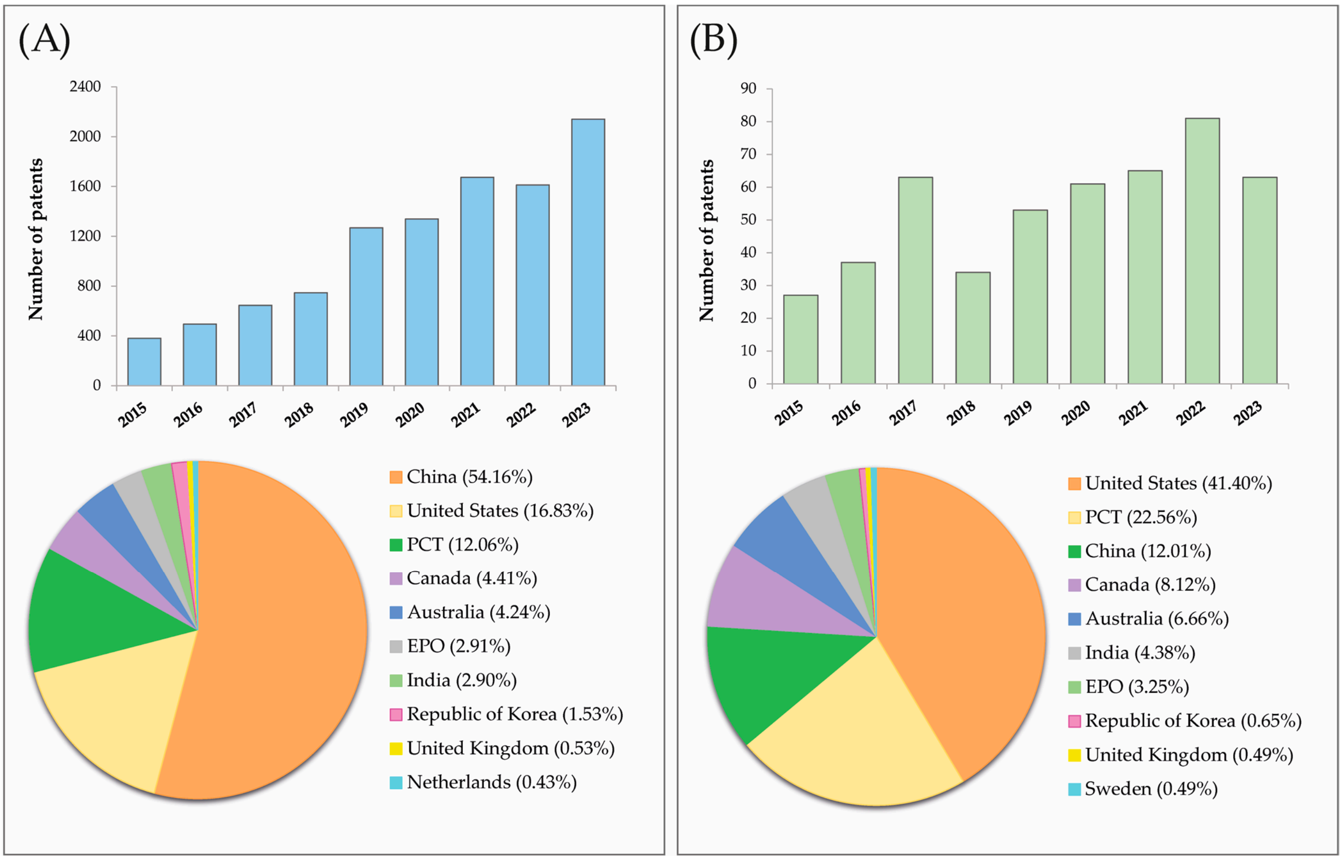

Figure 5. Relationship between the number of patents registered and the countries with the most deposits using the terms "biochar OR bio-char" (**A**) and "(biochar production) OR (bio-char production)" (**B**). Source: PATENTSCOPE, WIPO. PCT: Patent Cooperation Treaty; EPO: European Patent Office.

Among all registered documents, patents are mostly classified under two International Patent Classification (IPC) codes: C02F and B01J. The international classification is mainly used to organize patent documents to facilitate access to the technological and legal information contained in these documents. It also enables research to be focused on the technological area of interest.

Out of the 11,654 patent documents found for the terms "biochar OR bio-char", 2974 are classified under code C02F, which corresponds to section C (chemistry; metallurgy), and Class 02 and Subclass F of the same description (treatment of water, sewage, effluent or sludge). Therefore, the main focus of the technologies developed and classified under this code is the use of biochar in the treatment of water, wastewater, sewage, or sludge. For instance, a patent granted to the Hindusthan College of Engineering and Technology developed a biochar nano-sorbent embedded with magnetite for effective adsorption of the textile dye Levafix Blue [88]. In another study developed by the company Biochar Now, a system and method for removing pollutants from water bodies using biochar is reported [89].

The other code with a high number of patent applications is B01J, which corresponds to Section B (performing operations; transporting), Class 01 (physical or chemical processes or apparatus in general), and Subclass J (chemical or physical processes, e.g., catalysis or colloid chemistry; apparatus therefor), which mainly deals with new methods of treating and processing biochar. For example, a patent granted to Thermotech Combustion (2023) covers a biochar pyrolysis system comprising a batch pyrolyzer with an oven and a biochar chamber with syngas and a bio-oil outlet. The method of operation of this biochar pyrolysis system is also disclosed [90].

Furthermore, to refine the list of patents filed on biochar, a search was carried out using the terms "(biochar production) OR (bio-char production)", which returned 627 documents (Figure 2B). The class in which the most patents were granted was C10B that, according to the IPC, corresponds to Section C (chemistry; metallurgy), Class 10 (petroleum, gas or coke industries; industrial gases containing carbon monoxide; fuels; lubricants; peat) and Subclass B (destructive distillation of carbonaceous materials for the production of gas, coke, tar or similar materials) (Figure 5B).

Among the companies that filed the most patents, Cool Planet Energy Systems Inc. (54 patents), Carbon Technology Holdings (24 patents), and Biochar Now (22 patents) can be highlighted; all three companies are based in the United States. Cool Planet Energy Systems is a company that focuses on the production of biochar and other biomass-derived products for agricultural and environmental applications. Its last patent granted was in 2020, in which the invention refers to coating plant seeds with biochar before planting, to increase the effectiveness of plant seed germination [91]. Carbon Technology Holdings is a company that works with technology to convert biomass into hydrocarbon fuels, chemical products, and biocarbon. Its last patent granted was in 2023, and it refers to the use of biochar—treated and/or processed biochar—which has properties that improve physical and chemical processes, aiming to increase the utility, predictability, and effectiveness of treated biochar to reduce the environmental impact of agriculture [92]. Finally, Biochar Now is a company dedicated to producing high-quality biochar for use in agriculture, waste management, and other applications. Its last patent granted was in 2021, and it refers to the disclosure of a new set of lids for an oven and a portable biochar production system, to seek to further increase the quality of the biochar produced, given that the construction and variables of the biochar oven can directly influence the high quality of the product [93].

6. Biochar at the Industrial Level

Biochar is emerging as an important carbon commodity in various applications, being traded in increasing quantities globally. The market can be divided into segments based on process, raw material, and application [94]. From a technological point of view, slow pyrolysis currently dominates biochar production, with a market share of more than 70%, and is expected to present significant growth opportunities in the coming years [95]. In the past decade, new applications for biochar—e.g., construction, high-tech materials, livestock, medicine, and water and air purification [96]—have driven growth in the sector, especially in China, the United States, and Europe [94].

The growing number of biochar industries around the world reflects the increasing recognition of the environmental and economic advantages of this product. Table 2 provides an overview of some biochar industries worldwide by presenting their location, starting year, capacity, process, and feedstock.

Table 2. Some biochar industries worldwide.

Company	Location	Starting Year	Production Capacity (Ton/Year)	Process	Feedstock
Airex Energy	Bécancour, QC, Canada	2024 **	10,000	Pyrolysis	Wood waste and forest biomass
Antaco	London, UK	2014	500	HTC	Organic waste
Aries Clean Energy	Franklin, TN, USA	2016	3500	Gasification	Mixture of wood waste
Arigna Fuels	Carrick On Shannon, Ireland	2019	5000	Pyrolysis	Mixed agricultural waste
Carbo Culture	Helsinki, Finland	2023	940	Pyrolysis	Wood waste
Carbofex	Nokia, Finland	2017	2000	Pyrolysis	Wood waste
Carbonis	Garrel, Germany	2016	360	Gasification	Wood waste
CharTech Solutions	Toronto, ON, Canada	2024 **	2000	Pyrolysis	-
CPL Industries	Immingham, UK	2025 **	2700	HTC	Organic waste
Circular Carbon	Straubing, Germany	2023	3500	Pyrolysis	Agricultural waste
Coaltec Energy	Evansville, IN, USA	2012	3000	Gasification	Manure and distillery grains
ECOERA	Falkenberg, Sweden	2019	300	Pyrolysis	Agricultural waste
Husk Ventures	Kampong Thom, Cambodia	2017	1400	Pyrolysis	Agricultural waste
Ingelia	Valencia, Spain	2017	6800 *	HTC	Sewage sludge, urban organic waste
Meva Energy	Gothenburg, Sweden	2023	6000	Gasification	Wood waste
Netzero	Rio Casca, Brazil	2023	4500	Pyrolysis	Agricultural waste
Netzero	Nkongsamba, Cameroon	2022	2000	Pyrolysis	Agricultural waste
Novocarbo	Hamburg, Germany	2023	1700	Pyrolysis	Wood waste
SoMax	Spring City, PA, USA	2022	1500	HTC	Swage sludge
TerraNova Energy	Solina, Poland	2024 **	450	HTC	Sewage sludge, urban organic waste

* Estimated value based on the amount of waste processed, with a yield of 48.7% [37]. ** In construction/implementation phase.

Accordingly, biochar has been produced by companies in several countries, using different raw materials, such as forestry and agricultural waste, and production techniques (pyrolysis, gasification, and HTC). It is important to note, however, that those industries are predominantly in economically developed countries, which have dominated the production technologies.

In order to take advantage of the waste available in each territory, biochar companies use the most abundant raw materials. For instance, Airex Energy employs byproducts from sawmills, wood waste, and forest biomass as feedstock. The company has invested $38 million in a biochar production project in Quebec, Canada, in collaboration with the SUEZ Group, and its goal is to develop a production facility with a capacity of 30,000 tons per year, divided into three phases of 10,000 tons per year. The intention is to start operations by the end of the first quarter of 2024, with the phases planned to be fully completed by 2026.

Airex Energy is looking to expand its operations for future projects, to reach 350,000 tons per year by the year 2035, with Europe and North America being the target markets [97]. Another example is Meva Energy, which started its operations in the second quarter of 2023 at the Sofidel textile mill in Kisa, Sweden, producing biochar from local wood waste through the gasification process. It is estimated that a total of 10,300 tons of CO_2 will be reduced per year from the biochar generated, and the plant has replaced fossil gas consumption in the textile factory with renewable gas [98].

In Brazil, NetZero is in the state of Minas Gerais. It is the first industrial unit in South America entirely dedicated to the production of biochar and the largest in the world that uses only agricultural waste. The company officially opened on 20 April 2023. The raw material (coffee husks) is supplied with the help of local partners—Coocafé, which is a cooperative of around 10,000 producers. The biochar produced is sold to Coocafé farmers to help them reduce their use of fertilizers while increasing their yields and the health of their soils. The company's production capacity reaches 4500 tons of biochar per year. It is currently building Brazil's second plant in the state of Espírito Santo, with a biochar production capacity like the first one.

7. Brazilian Potential Biochar Production—Waste Biomass Availability

In the Brazilian context, the potential to produce biochar could be a promising solution for dealing with a variety of residues from different sectors [99]. It is known that biochar production is also dependent on the availability and quantity of raw materials. The source could be agricultural and forestry waste, sewage sludge from municipal WWTP, and MSW [100]. Moreover, Brazil has a vast production of agricultural and forestry waste [101], as well as WWTP sewage sludge and MSW [102–104], which also stand out as potential sources for biochar production.

The annual production of Brazilian agriculture is significant, as Brazil is one of the largest agricultural producers in the world [105]. The country has a vast arable area, with 340 million hectares, of which 63 million hectares are agricultural areas [106]. Thus, the significantly high generation of agricultural waste from different crops is inevitable—sugarcane, soy, corn, cassava, cotton, orange, beans, rice, wheat, and coffee—as reported in Table 3. Brazil is also known for its livestock production, which is another source of waste. The estimated waste generation from livestock is presented in Table 4.

Table 3. Estimated waste generated from the most significant crops in Brazil.

Crop	Production (Mton/Year) [a]	Waste [b]	Estimated Waste Generated (Mton/Year)
Sugarcane	724.4	64% (30%—bagasse; 34%—straw and leaves)	463.6
Soy	120.7	150% (bark, stems, and leaves)	181.0
Corn	109.4	120% (20%—germ and envelopes; 78%—straw, stems, and leaves; 22%—corncob)	131.3
Cassava	17.6	216% (16%—bran; 200%—straw, stems, and leaves)	38.0
Cotton	6.4	278% (straw, stems, and leaves)	17.8
Orange	16.9	50% (bagasse, bark, and seeds)	8.5
Beans	2.8	116% (straw, stems, and leaves)	3.2
Rice	10.8	23% (husks)	2.5
Wheat	10.3	23% (bran)	2.4
Coffee	3.2	55% (husks)	1.8
Total			850.1

[a] [107]; [b] [108–112].

Table 4. Estimation of the most significant wastes generated by livestock in Brazil.

Livestock	Number of Heads [a]	Amount of Manure Per Day Per Animal (Kg) [b]	Estimated Availability of Manure (%) [b]	Estimated Waste Generated (Mton/Year)
Cattle	234,352,649	27.8	47.3	1124.8
Swine	44,393,930	2.96	89.5	42.9
Poultry (chickens and quails)	1,600,076,425	0.0275	80.0	12.8
Buffalo	1,598,268	40.0	50.0	11.7
Equines	5,834,544	13.8	29.0	8.5
Goats and Sheep	33,880,507	1.45	11.5	2.1
Total				1202.8

[a] [107]; [b] [113].

In addition to crop and livestock wastes, there are other widely available waste biomasses in Brazil: forestry residues, sewage sludge from WWTP, and MSW. Regarding forestry residues, Brazil's production of roundwood from planted forests reached almost 158.3 million cubic meters in 2022 [114]. In 2018, it was estimated that about 8.2 million tons of wood processing waste were produced [115]. Thus, given their content of cellulose, hemicellulose, and lignin, these residues have the potential to be used in other processes [116–118]. The sewage sludge from municipal WWTP is another waste produced in large amounts. Estimates suggest that 2.5 million tons of sewage sludge are produced in Brazil annually [119]. The MSW generated in the country has increased over the years to an estimated 81.8 million tons in 2022 [120].

Considering the waste generated by several activities, producing biochar is a possibility for waste treatment and valorization. Recent studies have proposed biochar production from agricultural waste, such as sugarcane bagasse [121], soy [122], corn [123], cassava [124], cotton [125], and orange [126]. Biochar can also be obtained from livestock waste, as reported for cattle [127], swine [128], and poultry [129] manures. Forestry waste is another type of waste suitable to produce biochar [38,130], as well as sewage sludge from WWTP [131] and MSW [132].

Before reaching the industrial level, however, studies addressing techno-economic analysis (TEA) and life cycle assessment (LCA) are crucial to evaluate the economic and environmental feasibility of the process, respectively [7]. The discussion proposed herein emphasizes the Brazilian potential to supply raw materials to be converted into biochar. Nevertheless, TEA and LCA must be performed to ensure the sustainability of biochar production from economic and environmental perspectives. TEA is essential to identify the profitability of the biochar production process and bring it to market [133]. Operating, raw material collection, equipment, and manufacturing costs are important characteristics of any process or product in terms of technical and economic performance, and therefore they need to be evaluated. Besides, alongside these costs, energy efficiency is always a crucial factor in determining the economic viability of the process [134]. Regarding LCA, it is a methodology that systematically assesses the environmental impacts of a product, process, or service throughout all its phases, from the extraction of raw materials to final disposal [135]. In the context of biochar, this approach is important for understanding the environmental effects associated with the production, transportation, application, and eventual disposal of this carbonaceous material.

8. Biochar and the Sustainable Development Goals (SDGs)

The SDGs are a set of 17 targets drawn up by the United Nations in 2015 to deal with environmental, economic, and sociopolitical issues. The goals have been subdivided into 169 targets, and 2030 was established as the deadline for achieving them [136]. Reaching these goals will be crucial to preserving the planet from the threats that continually damage the environment [137]. Thus, technologies that contribute to achieving some of the SDGs are fundamental. Regarding biochar, it is possible to point out its potential contribution to some of the SDGs. Herein are considered goals 6 (Clean water and sanitation), 7 (Affordable and clean energy), and 13 (Climate action), for which biochar production and application might have a direct impact.

Regarding SDG 6, biochar can be used for water and wastewater treatment. Gwenzi and co-workers highlighted that, given the biochar capacity of removing pollutants from aqueous solutions, it can be considered as a technology for drinking water treatment. Indeed, biochar is a low-cost and renewable adsorbent, which could be appropriate for low-income communities. Furthermore, it can remove physical, chemical, and biological contaminants while maintaining the organoleptic properties of the water [138]. For wastewater treatment, biochar can also be an option, since it has been extensively tested as an adsorbent to remove heavy metals, organic pollutants, and nutrients from wastewater. Therefore, biochar is suggested as an efficient material to treat several effluents such as municipal, industrial, and agricultural wastewater as well as stormwater [139].

As a solid biofuel, biochar can also be used to achieve SDG 7. For instance, the calorific value of agricultural waste biochar produced at 250, 350, and 450 °C is about 24 MJ/kg [140]. Biochar can also be mixed with fossil fuels to improve the combustion process instead of being burnt alone. It was reported that fossil fuels mixed with biochar in equal proportions showed increased combustion efficiency and improved thermal characteristics compared to coal fuels. In addition, soot yield, CO emissions, and unburned carbon in the ash were significantly reduced in fossil fuels blended with biochar. The potential for volatilization of potentially toxic elements during the combustion of biochar and its mixtures with coal decreased by up to 21% compared to burning coal alone [141]. Therefore, biochar is a promising solid biofuel, which can provide clean and renewable energy.

The environmental benefits of biochar production are evident, given the raw material used in its production (highly available waste) and its environmentally oriented applications. Thus, one can say that biochar production and utilization are aligned with SDG 13. Nowadays, the global community has committed itself to adopting sustainable strategies to reduce greenhouse gas emissions, promote renewable energies, and implement policies and practices that guarantee adaptation and resilience to the challenges posed by climate change. In this sense, biochar has been recognized as a promising technology for contributing to climate change mitigation and achieving SDG 13 [140]. Indeed, biochar production is a way of carbon sequestration when applied to soils [142]. Besides, carbon sequestration is not only considered an efficient CO_2 removal technology but also improves soil quality by enhancing ecosystem functions and services, food security, and resilience to climate change [143].

Accordingly, it is undeniable that biochar has the potential to contribute to the SDGs' achievement. Biochar has emerged as a multifunctional technology, which can assist water and wastewater treatment, provide clean energy production, and promote carbon sequestration. It offers, therefore, effective and sustainable solutions to contemporary environmental challenges.

9. Conclusions

This overview shows a growing interest in biochar research in the past 10 years. The analysis of published research articles highlighted the leadership of China and the United States in biochar research. It suggests the importance of biochar as an environmentally favorable solution for the treatment and valorization of wastes. Besides being a solution for waste management, biochar can also be applied as an adsorbent material to capture pollutants from water and soils, as a solid biofuel for energy production, and to perform carbon sequestration. Concerning patent development, the United States and China are the main patent depositors, which may be attributed to the fact that these countries have assumed a leading role in biochar research. The increase in the number of patents demonstrates the interest in biochar production and represents a step towards consolidating the technology at an industrial scale. In that regard, the global biochar market has been growing, with increasing industrial production and diversification of applications. In the Brazilian context, a potential for biochar production has been identified regarding the availability of feedstocks (biomass wastes) in the country. Evidently, more studies, such as LCA and TEA, must be performed to demonstrate the environmental and economic feasibility of producing biochar in Brazil considering different scenarios. However, by producing biochar and applying it to manage environmental problems, it is possible to contribute to reaching some of the SDGs (Clean water and sanitation, Affordable and clean energy, and Climate action).

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References

1. 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]
2. Lehmann, J.; Gaunt, J.; Rondon, M. Bio-Char Sequestration in Terrestrial Ecosystems—A Review. *Mitig. Adapt. Strateg. Glob. Change* **2006**, *11*, 403–427. [CrossRef]
3. Zhang, Z.; Zhu, Z.; Shen, B.; Liu, L. Insights into Biochar and Hydrochar Production and Applications: A Review. *Energy* **2019**, *171*, 581–598. [CrossRef]
4. Abdeljaoued, E.; Brulé, M.; Tayibi, S.; Manolakos, D.; Oukarroum, A.; Monlau, F.; Barakat, A. Bibliometric Analysis of the Evolution of Biochar Research Trends and Scientific Production. *Clean. Technol. Environ. Policy* **2020**, *22*, 1967–1997. [CrossRef]
5. Ahmed, M.J.; Hameed, B.H. Insight into the Co-Pyrolysis of Different Blended Feedstocks to Biochar for the Adsorption of Organic and Inorganic Pollutants: A Review. *J. Clean. Prod.* **2020**, *265*, 121762. [CrossRef]
6. Ippolito, J.A.; Cui, L.; Kammann, C.; Wrage-Mönnig, N.; Estavillo, J.M.; Fuertes-Mendizabal, T.; Cayuela, M.L.; Sigua, G.; Novak, J.; Spokas, K.; et al. Feedstock Choice, Pyrolysis Temperature and Type Influence Biochar Characteristics: A Comprehensive Meta-Data Analysis Review. *Biochar* **2020**, *2*, 421–438. [CrossRef]
7. Cavali, M.; Libardi, N., Jr.; Mohedano, R.D.A.; Filho, P.B.; da Costa, R.H.R.; de Castilhos, A.B., Jr. Biochar and Hydrochar in the Context of Anaerobic Digestion for a Circular Approach: An Overview. *Sci. Total Environ.* **2022**, *822*, 153614. [CrossRef]
8. Tian, H.; Wei, Y.; Cheng, S.; Huang, Z.; Qing, M.; Chen, Y.; Yang, H.; Yang, Y. Optimizing the Gasification Reactivity of Biochar: The Composition, Structure and Kinetics of Biochar Derived from Biomass Lignocellulosic Components and Their Interactions during Gasification Process. *Fuel* **2022**, *324*, 124709. [CrossRef]
9. Al-Rumaihi, A.; Shahbaz, M.; Mckay, G.; Mackey, H.; Al-Ansari, T. A Review of Pyrolysis Technologies and Feedstock: A Blending Approach for Plastic and Biomass towards Optimum Biochar Yield. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112715. [CrossRef]
10. Cavali, M.; Libardi, N., Jr.; de Sena, J.D.; Woiciechowski, A.L.; Soccol, C.R.; Belli Filho, P.; Bayard, R.; Benbelkacem, H.; de Castilhos, A.B., Jr. A Review on Hydrothermal Carbonization of Potential Biomass Wastes, Characterization and Environmental Applications of Hydrochar, and Biorefinery Perspectives of the Process. *Sci. Total Environ.* **2023**, *857*, 159627. [CrossRef]
11. Nakason, K.; Khemthong, P.; Panyapinyopol, B. Torrefaction of Agricultural Wastes: Influence of Lignocellulosic Types and Treatment Temperature on Fuel Properties of Biochar. *Int. Energy J.* **2019**, *19*, 253–266.
12. Carvalho, J.; Nascimento, L.; Soares, M.; Valério, N.; Ribeiro, A.; Faria, L.; Silva, A.; Pacheco, N.; Araújo, J.; Vilarinho, C. Life Cycle Assessment (LCA) of Biochar Production from a Circular Economy Perspective. *Processes* **2022**, *10*, 2684. [CrossRef]
13. Hussin, F.; Hazani, N.N.; Khalil, M.; Aroua, M.K. Environmental Life Cycle Assessment of Biomass Conversion Using Hydrothermal Technology: A Review. *Fuel Process. Technol.* **2023**, *246*, 107747. [CrossRef]
14. Sahoo, K.; Upadhyay, A.; Runge, T.; Bergman, R.; Puettmann, M.; Bilek, E. Life-Cycle Assessment and Techno-Economic Analysis of Biochar Produced from Forest Residues Using Portable Systems. *Int. J. Life Cycle Assess* **2020**, *26*, 189–213. [CrossRef]
15. Bergman, R.; Sahoo, K.; Englund, K.; Mousavi-Avval, S.H. Lifecycle Assessment and Techno-Economic Analysis of Biochar Pellet Production from Forest Residues and Field Application. *Energies* **2022**, *15*, 1559. [CrossRef]
16. Nematian, M.; Keske, C.; Ng'ombe, J.N. A Techno-Economic Analysis of Biochar Production and the Bioeconomy for Orchard Biomass. *Waste Manag.* **2021**, *135*, 467–477. [CrossRef]
17. European Biochar Industry. *European Biochar—Market Report 2022/2023*; European Biochar Industry: Freiburg im Breisgau, Germany, 2023.

18. Precedence Research. *Biochar Market (By Technology: Pyrolysis, Gasification, Others; By Feedstock: Woody Biomass, Agricultural Waste, Animal Manure, Others; By Application: Agriculture, Forestry, Electricity Generation, Others)—Global Industry Analysis, Size, Share, Growth, Trends, Regional Outlook, and Forecast 2023–2032*; Precedence Research: Ottawa, ON, Canada, 2023.
19. Fortune Business Insights. *The Global Biochar Market Size Was Valued at $184.90 Million in 2022 & Is Projected to Grow from $204.69 Million in 2023 to $450.58 Million by 2030*; Fortune Business Insights: Pune, India, 2023.
20. Allied Market Research. *Biochar Market by Production Technology (Pyrolysis, Gasification, Others), by Application (Soil Amendment, Animal Feed, Industrial, Others): Global Opportunity Analysis and Industry Forecast, 2021–2031*; Allied Market Research: Pune, India, 2023.
21. Xiong, X.; He, M.; Dutta, S.; Tsang, D.C.W. Biochar and Sustainable Development Goals. In *Biochar in Agriculture for Achieving Sustainable Development Goals*; Academic Press: Cambridge, MA, USA, 2022; pp. 15–22, ISBN 9780323853439.
22. Padhye, L.P.; Bandala, E.R.; Wijesiri, B.; Goonetilleke, A.; Bolan, N. Hydrochar: A Promising Step Towards Achieving a Circular Economy and Sustainable Development Goals. *Front. Chem. Eng.* **2022**, *4*, 867228. [CrossRef]
23. Godlewska, P.; Schmidt, H.P.; Ok, Y.S.; Oleszczuk, P. Biochar for Composting Improvement and Contaminants Reduction. A Review. *Bioresour. Technol.* **2017**, *246*, 193–202. [CrossRef]
24. Rajapaksha, A.U.; Chen, S.S.; Tsang, D.C.W.; Zhang, M.; Vithanage, M.; Mandal, S.; Gao, B.; Bolan, N.S.; Ok, Y.S. Engineered/Designer Biochar for Contaminant Removal/Immobilization from Soil and Water: Potential and Implication of Biochar Modification. *Chemosphere* **2016**, *148*, 276–291. [CrossRef]
25. Wang, B.; Gao, B.; Fang, J. Recent Advances in Engineered Biochar Productions and Applications. *Crit. Rev. Environ. Sci. Technol.* **2018**, *47*, 2158–2207. [CrossRef]
26. Antor, N.H.; Mia, S.; Hasan, M.M.; Lipi, N.J.; Jindo, K.; Sanchez-Monedero, M.A.; Rashid, M.H. Chemically and Biologically Activated Biochars Slow down Urea Hydrolysis and Improve Nitrogen Use Efficiency. *Pedosphere* **2023**, *33*, 659–669. [CrossRef]
27. Zhang, S.; Xiong, Y. Washing Pretreatment with Light Bio-Oil and Its Effect on Pyrolysis Products of Bio-Oil and Biochar. *RSC Adv.* **2016**, *6*, 5270–5277. [CrossRef]
28. Raclavská, H.; Corsaro, A.; Juchelková, D.; Sassmanová, V.; Frantík, J. Effect of Temperature on the Enrichment and Volatility of 18 Elements during Pyrolysis of Biomass, Coal, and Tires. *Fuel Process. Technol.* **2015**, *131*, 330–337. [CrossRef]
29. Funke, A.; Demus, T.; Willms, T.; Schenke, L.; Echterhof, T.; Niebel, A.; Pfeifer, H.; Dahmen, N. Application of Fast Pyrolysis Char in an Electric Arc Furnace. *Fuel Process. Technol.* **2018**, *174*, 61–68. [CrossRef]
30. Zhou, X.; Moghaddam, T.B.; Chen, M.; Wu, S.; Zhang, Y.; Zhang, X.; Adhikari, S.; Zhang, X. Effects of Pyrolysis Parameters on Physicochemical Properties of Biochar and Bio-Oil and Application in Asphalt. *Sci. Total Environ.* **2021**, *780*, 146448. [CrossRef] [PubMed]
31. Vieira, F.R.; Romero Luna, C.M.; Arce, G.L.A.F.; Ávila, I. Optimization of Slow Pyrolysis Process Parameters Using a Fixed Bed Reactor for Biochar Yield from Rice Husk. *Biomass Bioenergy* **2020**, *132*, 105412. [CrossRef]
32. Setter, C.; Silva, F.T.M.; Assis, M.R.; Ataíde, C.H.; Trugilho, P.F.; Oliveira, T.J.P. Slow Pyrolysis of Coffee Husk Briquettes: Characterization of the Solid and Liquid Fractions. *Fuel* **2020**, *261*, 116420. [CrossRef]
33. Ronsse, F.; van Hecke, S.; Dickinson, D.; Prins, W. Production and Characterization of Slow Pyrolysis Biochar: Influence of Feedstock Type and Pyrolysis Conditions. *GCB Bioenergy* **2013**, *5*, 104–115. [CrossRef]
34. Hossain, M.Z.; Bahar, M.M.; Sarkar, B.; Donne, S.W.; Wade, P.; Bolan, N. Assessment of the Fertilizer Potential of Biochars Produced from Slow Pyrolysis of Biosolid and Animal Manures. *J. Anal. Appl. Pyrolysis* **2021**, *155*, 105043. [CrossRef]
35. Heidari, M.; Salaudeen, S.; Arku, P.; Acharya, B.; Tasnim, S.; Dutta, A. Development of a Mathematical Model for Hydrothermal Carbonization of Biomass: Comparison of Experimental Measurements with Model Predictions. *Energy* **2021**, *214*, 119020. [CrossRef]
36. Miliotti, E.; Casini, D.; Rosi, L.; Lotti, G.; Rizzo, A.M.; Chiaramonti, D. Lab-Scale Pyrolysis and Hydrothermal Carbonization of Biomass Digestate: Characterization of Solid Products and Compliance with Biochar Standards. *Biomass Bioenergy* **2020**, *139*, 105593. [CrossRef]
37. Merzari, F.; Lucian, M.; Volpe, M.; Andreottola, G.; Fiori, L. Hydrothermal Carbonization of Biomass: Design of a Bench-Scale Reactor for Evaluating the Heat of Reaction. *Chem. Eng. Trans.* **2018**, *65*, 43–48. [CrossRef]
38. Cavali, M.; Benbelkacem, H.; Kim, B.; Bayard, R.; Libardi, N., Jr.; Gonzaga Domingos, D.; Woiciechowski, A.L.; de Castilhos, A.B., Jr. Co-Hydrothermal Carbonization of Pine Residual Sawdust and Non-Dewatered Sewage Sludge—Effect of Reaction Conditions on Hydrochar Characteristics. *J. Environ. Manag.* **2023**, *340*, 117994. [CrossRef] [PubMed]
39. Adeniyi, A.G.; Ighalo, J.O.; Onifade, D.V. Production of Biochar from Elephant Grass (*Pernisetum purpureum*) Using an Updraft Biomass Gasifier with Retort Heating. *Biofuels* **2021**, *12*, 1283–1290. [CrossRef]
40. Hernández, J.J.; Saffe, A.; Collado, R.; Monedero, E. Recirculation of Char from Biomass Gasification: Effects on Gasifier Performance and End-Char Properties. *Renew. Energy* **2020**, *147*, 806–813. [CrossRef]
41. Tian, H.; Hu, Q.; Wang, J.; Chen, D.; Yang, Y.; Bridgwater, A.V. Kinetic Study on the CO_2 Gasification of Biochar Derived from Miscanthus at Different Processing Conditions. *Energy* **2021**, *217*, 119341. [CrossRef]
42. Arriola, E.; Chen, W.H.; Chih, Y.K.; De Luna, M.D.; Show, P.L. Impact of Post-Torrefaction Process on Biochar Formation from Wood Pellets and Self-Heating Phenomena for Production Safety. *Energy* **2020**, *207*, 118324. [CrossRef]
43. Zhang, C.; Ho, S.H.; Chen, W.H.; Xie, Y.; Liu, Z.; Chang, J.S. Torrefaction Performance and Energy Usage of Biomass Wastes and Their Correlations with Torrefaction Severity Index. *Appl. Energy* **2018**, *220*, 598–604. [CrossRef]

44. Liu, X.; Li, Z.; Zhang, Y.; Feng, R.; Mahmood, I.B. Characterization of Human Manure-Derived Biochar and Energy-Balance Analysis of Slow Pyrolysis Process. *Waste Manag.* **2014**, *34*, 1619–1626. [CrossRef]
45. Kung, C.-C.; Mu, J.E. Prospect of China's Renewable Energy Development from Pyrolysis and Biochar Applications under Climate Change. *Renew. Sustain. Energy Rev.* **2019**, *114*, 109343. [CrossRef]
46. Foong, S.Y.; Liew, R.K.; Yang, Y.; Cheng, Y.W.; Yek, P.N.Y.; Wan Mahari, W.A.; Lee, X.Y.; Han, C.S.; Vo, D.-V.N.; Van Le, Q.; et al. Valorization of Biomass Waste to Engineered Activated Biochar by Microwave Pyrolysis: Progress, Challenges, and Future Directions. *Chem. Eng. J.* **2020**, *389*, 124401. [CrossRef]
47. Russell, S.H.; Turrion-Gomez, J.L.; Meredith, W.; Langston, P.; Snape, C.E. Increased Charcoal Yield and Production of Lighter Oils from the Slow Pyrolysis of Biomass. *J. Anal. Appl. Pyrolysis* **2017**, *124*, 536–541. [CrossRef]
48. Al Arni, S. Comparison of Slow and Fast Pyrolysis for Converting Biomass into Fuel. *Renew. Energy* **2018**, *124*, 197–201. [CrossRef]
49. Qian, K.; Kumar, A.; Zhang, H.; Bellmer, D.; Huhnke, R. Recent Advances in Utilization of Biochar. *Renew. Sustain. Energy Rev.* **2015**, *42*, 1055–1064. [CrossRef]
50. Garcia-Nunez, J.A.; Pelaez-Samaniego, M.R.; Garcia-Perez, M.E.; Fonts, I.; Abrego, J.; Westerhof, R.J.M.; Garcia-Perez, M. Historical Developments of Pyrolysis Reactors: A Review. *Energy Fuels* **2017**, *31*, 5751–5775. [CrossRef]
51. Lee, J.; Lee, K.; Sohn, D.; Kim, Y.M.; Park, K.Y. Hydrothermal Carbonization of Lipid Extracted Algae for Hydrochar Production and Feasibility of Using Hydrochar as a Solid Fuel. *Energy* **2018**, *153*, 913–920. [CrossRef]
52. Yan, W.; Hastings, J.T.; Acharjee, T.C.; Coronella, C.J.; Vásquez, V.R. Mass and Energy Balances of Wet Torrefaction of Lignocellulosic Biomass. *Energy Fuels* **2010**, *24*, 4738–4742. [CrossRef]
53. Oliveira, I.; Blöhse, D.; Ramke, H.-G. Hydrothermal Carbonization of Agricultural Residues. *Bioresour. Technol.* **2013**, *142*, 138–146. [CrossRef]
54. Tan, P.; Zhang, C.; Xia, J.; Fang, Q.Y.; Chen, G. Estimation of Higher Heating Value of Coal Based on Proximate Analysis Using Support Vector Regression. *Fuel Process. Technol.* **2015**, *138*, 298–304. [CrossRef]
55. Mohan, D.; Sarswat, A.; Ok, Y.S.; Pittman, C.U. Organic and Inorganic Contaminants Removal from Water with Biochar, a Renewable, Low Cost and Sustainable Adsorbent—A Critical Review. *Bioresour. Technol.* **2014**, *160*, 191–202. [CrossRef]
56. Sharma, A.K.; Ghodke, P.K.; Goyal, N.; Bobde, P.; Kwon, E.E.; Lin, K.Y.A.; Chen, W.H. A Critical Review on Biochar Production from Pine Wastes, Upgradation Techniques, Environmental Sustainability, and Challenges. *Bioresour. Technol.* **2023**, *387*, 129632. [CrossRef] [PubMed]
57. Chen, W.H.; Peng, J.; Bi, X.T. A State-of-the-Art Review of Biomass Torrefaction, Densification and Applications. *Renew. Sustain. Energy Rev.* **2015**, *44*, 847–866. [CrossRef]
58. Spinosa, L.; Carella, C.; Spinosa, L.; Carella, C. Planning the Management of Municipal Solid Waste: The Case of Region "Puglia (Apulia)" in Italy. *Integr. Waste Manag.* **2011**, *1*, 55–78. [CrossRef]
59. Yusop, Y.M.; Othman, N. Linking the Malaysia's Solid Waste Management Policy Instruments with Household Recycling Behavior. *Int. J. Acad. Res. Progress. Educ. Dev.* **2019**, *8*, 474–488. [CrossRef]
60. Wichelns, D.; Drechsel, P.; Qadir, M. Wastewater: Economic Asset in an Urbanizing World. In *Wastewater: Economic Asset in an Urbanizing World*; Springer: Berlin/Heidelberg, Germany, 2015; pp. 3–14. [CrossRef]
61. Singh, S.; Kumar, V.; Dhanjal, D.S.; Datta, S.; Bhatia, D.; Dhiman, J.; Samuel, J.; Prasad, R.; Singh, J. A Sustainable Paradigm of Sewage Sludge Biochar: Valorization, Opportunities, Challenges and Future Prospects. *J. Clean. Prod.* **2020**, *269*, 122259. [CrossRef]
62. Callegari, A.; Capodaglio, A.G. Properties and Beneficial Uses of (Bio)Chars, with Special Attention to Products from Sewage Sludge Pyrolysis. *Resources* **2018**, *7*, 20. [CrossRef]
63. Huang, Z.; Zhang, X.; Peñuelas, J.; Sardans, J.; Jin, Q.; Wang, C.; Yang, L.; Fang, Y.; Li, Z.; Wang, W. Industrial and Agricultural Waste Amendments Interact with Microorganism Activities to Enhance P Availability in Rice-Paddy Soils. *Sci. Total Environ.* **2023**, *901*, 166364. [CrossRef]
64. Liu, Y.; Sidhu, K.S.; Chen, Z.; Yang, E.H. Alkali-Treated Incineration Bottom Ash as Supplementary Cementitious Materials. *Constr. Build. Mater.* **2018**, *179*, 371–378. [CrossRef]
65. Chen, L.; Wang, L.; Cho, D.W.; Tsang, D.C.W.; Tong, L.; Zhou, Y.; Yang, J.; Hu, Q.; Poon, C.S. Sustainable Stabilization/Solidification of Municipal Solid Waste Incinerator Fly Ash by Incorporation of Green Materials. *J. Clean. Prod.* **2019**, *222*, 335–343. [CrossRef]
66. Khan, N.; Chowdhary, P.; Gnansounou, E.; Chaturvedi, P. Biochar and Environmental Sustainability: Emerging Trends and Techno-Economic Perspectives. *Bioresour. Technol.* **2021**, *332*, 125102. [CrossRef]
67. Palansooriya, K.N.; Ok, Y.S.; Awad, Y.M.; Lee, S.S.; Sung, J.K.; Koutsospyros, A.; Moon, D.H. Impacts of Biochar Application on Upland Agriculture: A Review. *J. Environ. Manag.* **2019**, *234*, 52–64. [CrossRef] [PubMed]
68. Barquilha, C.E.R.; Braga, M.C.B. Adsorption of Organic and Inorganic Pollutants onto Biochars: Challenges, Operating Conditions, and Mechanisms. *Bioresour. Technol. Rep.* **2021**, *15*, 100728. [CrossRef]
69. Tan, X.; Liu, Y.; Zeng, G.; Wang, X.; Hu, X.; Gu, Y.; Yang, Z. Application of Biochar for the Removal of Pollutants from Aqueous Solutions. *Chemosphere* **2015**, *125*, 70–85. [CrossRef] [PubMed]
70. Cheng, S.; Chen, T.; Xu, W.; Huang, J.; Jiang, S.; Yan, B. Application Research of Biochar for the Remediation of Soil Heavy Metals Contamination: A Review. *Molecules* **2020**, *25*, 3167. [CrossRef] [PubMed]

71. Wilton, N.; Lyon-Marion, B.A.; Kamath, R.; McVey, K.; Pennell, K.D.; Robbat, A. Remediation of Heavy Hydrocarbon Impacted Soil Using Biopolymer and Polystyrene Foam Beads. *J. Hazard Mater.* **2018**, *349*, 153–159. [CrossRef] [PubMed]
72. Qiu, B.; Tao, X.; Wang, H.; Li, W.; Ding, X.; Chu, H. Biochar as a Low-Cost Adsorbent for Aqueous Heavy Metal Removal: A Review. *J. Anal. Appl. Pyrolysis* **2021**, *155*, 105081. [CrossRef]
73. Yadav, G.; Sekar, M.; Kim, S.H.; Geo, V.E.; Bhatia, S.K.; Sabir, J.S.M.; Chi, N.T.L.; Brindhadevi, K.; Pugazhendhi, A. Lipid Content, Biomass Density, Fatty Acid as Selection Markers for Evaluating the Suitability of Four Fast Growing Cyanobacterial Strains for Biodiesel Production. *Bioresour. Technol.* **2021**, *325*, 124654. [CrossRef] [PubMed]
74. Perera, F. Pollution from Fossil-Fuel Combustion Is the Leading Environmental Threat to Global Pediatric Health and Equity: Solutions Exist. *Int. J. Environ. Res. Public Health* **2017**, *15*, 16. [CrossRef] [PubMed]
75. Basu, P. Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory. In *Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory*; Academic Press: Cambridge, MA, USA, 2013; pp. 1–530. [CrossRef]
76. Wyn, H.K.; Zárate, S.; Carrascal, J.; Yermán, L. A Novel Approach to the Production of Biochar with Improved Fuel Characteristics from Biomass Waste. *Waste Biomass Valorization* **2020**, *11*, 6467–6481. [CrossRef]
77. Patel, S.; Kundu, S.; Halder, P.; Ratnnayake, N.; Marzbali, M.H.; Aktar, S.; Selezneva, E.; Paz-Ferreiro, J.; Surapaneni, A.; de Figueiredo, C.C.; et al. *A Critical Literature Review on Biosolids to Biochar: An Alternative Biosolids Management Option*; Springer: Berlin/Heidelberg, Germany, 2020; Volume 19, ISBN 1115702009.
78. Saravanan, A.; Senthil Kumar, P.; Khoo, K.S.; Show, P.L.; Femina Carolin, C.; Fetcia Jackulin, C.; Jeevanantham, S.; Karishma, S.; Show, K.Y.; Lee, D.J.; et al. Biohydrogen from Organic Wastes as a Clean and Environment-Friendly Energy Source: Production Pathways, Feedstock Types, and Future Prospects. *Bioresour. Technol.* **2021**, *342*, 126021. [CrossRef]
79. Selvarajoo, A.; Wong, Y.L.; Khoo, K.S.; Chen, W.H.; Show, P.L. Biochar Production via Pyrolysis of Citrus Peel Fruit Waste as a Potential Usage as Solid Biofuel. *Chemosphere* **2022**, *294*, 133671. [CrossRef] [PubMed]
80. Cai, N.; Zhang, H.; Nie, J.; Deng, Y.; Baeyens, J. Biochar from Biomass Slow Pyrolysis. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2020; Volume 586. [CrossRef]
81. Saletnik, B.; Zagula, G.; Bajcar, M.; Tarapatskyy, M.; Bobula, G.; Puchalski, C. Biochar as a Multifunctional Component of the Environment-a Review. *Appl. Sci.* **2019**, *9*, 1139. [CrossRef]
82. Yang, Q.; Mašek, O.; Zhao, L.; Nan, H.; Yu, S.; Yin, J.; Li, Z.; Cao, X. Country-Level Potential of Carbon Sequestration and Environmental Benefits by Utilizing Crop Residues for Biochar Implementation. *Appl. Energy* **2021**, *282*, 116275. [CrossRef]
83. Wu, P.; Singh, B.P.; Wang, H.; Jia, Z.; Wang, Y.; Chen, W. Bibliometric Analysis of Biochar Research in 2021: A Critical Review for Development, Hotspots and Trend Directions. *Biochar* **2023**, *5*, 6. [CrossRef]
84. Zhang, X.; Yang, X.; Yuan, X.; Tian, S.; Wang, X.; Zhang, H.; Han, L. Effect of Pyrolysis Temperature on Composition, Carbon Fraction and Abiotic Stability of Straw Biochars: Correlation and Quantitative Analysis. *Carbon Res.* **2022**, *1*, 17. [CrossRef]
85. Xu, Z.; He, M.; Xu, X.; Cao, X.; Tsang, D.C.W. Impacts of Different Activation Processes on the Carbon Stability of Biochar for Oxidation Resistance. *Bioresour. Technol.* **2021**, *338*, 125555. [CrossRef] [PubMed]
86. Guenet, B.; Gabrielle, B.; Chenu, C.; Arrouays, D.; Balesdent, J.; Bernoux, M.; Bruni, E.; Caliman, J.P.; Cardinael, R.; Chen, S.; et al. Can N_2O Emissions Offset the Benefits from Soil Organic Carbon Storage? *Glob. Change Biol.* **2021**, *27*, 237–256. [CrossRef] [PubMed]
87. Yang, Q.; Zhou, H.; Bartocci, P.; Fantozzi, F.; Mašek, O.; Agblevor, F.A.; Wei, Z.; Yang, H.; Chen, H.; Lu, X.; et al. Prospective Contributions of Biomass Pyrolysis to China's 2050 Carbon Reduction and Renewable Energy Goals. *Nat. Commun.* **2021**, *12*, 1698. [CrossRef] [PubMed]
88. Magudeswaran, N.; Jaya, J.; Dineshkumar, M.; Rajkumar, A.; Induja, P.; Nithyanandam, C.; Senthil Murugan, V.; Sriharish, K. Magnetite Embedded Biochar as Nano-Sorbent for Effective Adsorption of Textile Dye and the Method Thereof. 202241028399A, 17 June 2022.
89. Beierwaltes, W.T.; Gaspard, J.G. Contaminant Removal from Water Bodies with Biochar. WO2023283744A1, 11 August 2016.
90. St-Pierre, D. Biochar Pyrolysis System and Method for Operating a Biochar Pyrolysis System. WO2023283744A1, 19 January 2023.
91. Traxler, V.S.; Kim, H.S.; Malyala, R.; Thompson, T.A.; Buege, B.; Jarand, M.L. Biochar Coated Seeds. US2020/0255353A1, 13 August 2020.
92. MacKay, J.; Belcher, R.W.; Bolsen, W.J.; Buege, B.; Daugaard, D.E.; Kim, H.S. Reducing the Environmental Impact of Farming Using Biochar. US20230125341A1, 27 April 2023.
93. Olander, M.; Pierce, P.; Beierwaltes, W.T.; Gaspard, J.G. Lid Assembly for Portable Biochar Kiln. US20200078956A1, 12 March 2020.
94. Garcia, B.; Alves, O.; Rijo, B.; Lourinho, G.; Nobre, C. Biochar: Production, Applications, and Market Prospects in Portugal. *Environments* **2022**, *9*, 95. [CrossRef]
95. González-Pernas, F.M.; Grajera-Antolín, C.; García-Cámara, O.; González-Lucas, M.; Martín, M.T.; González-Egido, S.; Aguirre, J.L. Effects of Biochar on Biointensive Horticultural Crops and Its Economic Viability in the Mediterranean Climate. *Energies* **2022**, *15*, 3407. [CrossRef]
96. EBI. Beyond Carbon Sequestration: The Wide-Ranging Applications of Biochar. Available online: https://www.biochar-industry.com/2023/2023-biochar-use-cases/ (accessed on 12 November 2023).
97. Sokic, N. *Sustainable BIZ Canada*. 2023. Available online: https://sustainablebiz.ca/airex-energy-completes-38m-funding-que-biochar-project (accessed on 14 October 2023).

98. Meva Energy Disponível Em. Available online: https://Mevaenergy.Com/Home/Our-Technology/Sofidel-Kisa-Plant/ (accessed on 23 October 2023).
99. Gonzaga, M.I.S.; de Souza, D.C.F.; de Santos, J.C.J. Use of Organic Waste Biochar as an Innovative Alternative for Increasing Agricultural Productivity in Small Rural Communities. *Res. Soc. Dev.* **2021**, *10*, e8910413848. [CrossRef]
100. Gupta, S.; Sireesha, S.; Sreedhar, I.; Patel, C.M.; Anitha, K.L. Latest Trends in Heavy Metal Removal from Wastewater by Biochar Based Sorbents. *J. Water Process Eng.* **2020**, *38*, 101561. [CrossRef]
101. Amorim, E.P.; Pimenta, A.S.; de Souza, E.C. Aproveitamento Dos Resíduos Da Colheita Florestal: Estado Da Arte e Oportunidades. *Res. Soc. Dev.* **2021**, *10*, e4410212175. [CrossRef]
102. Delgado-Moreno, L.; Bazhari, S.; Gasco, G.; Méndez, A.; El Azzouzi, M.; Romero, E. New Insights into the Efficient Removal of Emerging Contaminants by Biochars and Hydrochars Derived from Olive Oil Wastes. *Sci. Total Environ.* **2021**, *752*, 141838. [CrossRef]
103. de Chernicharo, C.A.; Ribeiro, T.B.; Pegorini, E.S.; Possetti, G.R.C.; Miki, M.K.; de Souza, S.N. Contribuição Para o Aprimoramento de Projeto, Construção e Operação de Reatores UASB Aplicados Ao Tratamento de Esgoto Sanitário—Parte 1: Tópicos de Interesse. *Rev. DAE* **2018**, *66*, 5–16. [CrossRef]
104. Ferreira, M.M.; Fiore, F.A.; Saron, A.; da Silva, G.H.R. Systematic Review of the Last 20 Years of Research on Decentralized Domestic Wastewater Treatment in Brazil: State of the Art and Potentials. *Water Sci. Technol.* **2021**, *84*, 3469–3488. [CrossRef]
105. Santos, T.G.; Battisti, R.; Casaroli, D.; Alves, J.; Evangelista, A.W.P. Assessment of Agricultural Efficiency and Yield Gap for Soybean in the Brazilian Central Cerrado Biome. *Bragantia* **2021**, *80*, e1821. [CrossRef]
106. Clemente, A.M.; De Carvalho, O.A.; Guimaraes, R.F.; McManus, C.; Turazi, C.M.V.; Hermuche, P.M. Spatial-Temporal Patterns of Bean Crop in Brazil over the Period 1990–2013. *ISPRS Int. J. Geoinf.* **2017**, *6*, 107. [CrossRef]
107. IBGE Produção Agropecuária. 2022. Available online: https://www.ibge.gov.br/explica/producao-agropecuaria/br (accessed on 10 November 2023).
108. Ferreira-Leitao, V.; Gottschalk, L.M.F.; Ferrara, M.A.; Nepomuceno, A.L.; Molinari, H.B.C.; Bon, E.P.S. Biomass Residues in Brazil: Availability and Potential Uses. *Waste Biomass Valorization* **2010**, *1*, 65–76. [CrossRef]
109. Mendoza Martinez, C.L.; Saari, J.; Melo, Y.; Cardoso, M.; de Almeida, G.M.; Vakkilainen, E. Evaluation of Thermochemical Routes for the Valorization of Solid Coffee Residues to Produce Biofuels: A Brazilian Case. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110585. [CrossRef]
110. Hamawand, I.; Sandell, G.; Pittaway, P.; Chakrabarty, S.; Yusaf, T.; Chen, G.; Seneweera, S.; Al-Lwayzy, S.; Bennett, J.; Hopf, J. Bioenergy from Cotton Industry Wastes: A Review and Potential. *Renew. Sustain. Energy Rev.* **2016**, *66*, 435–448. [CrossRef]
111. Gómez, L.D.; Amalfitano, C.; Andolfi, A.; Simister, R.; Somma, S.; Ercolano, M.R.; Borrelli, C.; McQueen-Mason, S.J.; Frusciante, L.; Cuciniello, A.; et al. Valorising Faba Bean Residual Biomass: Effect of Farming System and Planting Time on the Potential for Biofuel Production. *Biomass Bioenergy* **2017**, *107*, 227–232. [CrossRef]
112. De Pretto, C.; Giordano, R.d.L.C.; Tardioli, P.W.; Costa, C.B.B. Possibilities for Producing Energy, Fuels, and Chemicals from Soybean: A Biorefinery Concept. *Waste Biomass Valorization* **2018**, *9*, 1703–1730. [CrossRef]
113. de Oliveira, A.C.L.; Milagres, R.S.; Orlando, W.d.A., Jr.; Renato, N.d.S. Evaluation of Brazilian Potential for Generating Electricity through Animal Manure and Sewage. *Biomass Bioenergy* **2020**, *139*, 105654. [CrossRef]
114. IBGE. Produção da Extração Vegetal e da Silvicultura. 2022. Available online: https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9105-producao-da-extracao-vegetal-e-da-silvicultura.html?edicao=37955&t=destaques (accessed on 12 November 2023).
115. Ferreira, T.V.B. *Potencial Energético de Resíduos Florestais do Manejo Sustentável e de Resíduos da Industrialização da Madeira*; Empresa de Pesquisa Energética, Ministério de Minas e Energia: Brasilia, Brazil, 2018. Available online: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-312/NT-EPE_17-2018_Biomassa-Lenhosa-Residual_2018-10-17.pdf (accessed on 12 November 2023).
116. Cavali, M.; Soccol, C.R.; Tavares, D.; Zevallos Torres, L.A.; Oliveira de Andrade Tanobe, V.; Zandoná Filho, A.; Woiciechowski, A.L. Valorization of Lignin from Pine (*Pinus* spp.) Residual Sawdust: Antioxidant Activity and Application in the Green Synthesis of Silver Nanoparticles for Antibacterial Purpose. *Biomass Convers. Biorefinery* **2021**, *13*, 10051–10063. [CrossRef]
117. Cavali, M.; Ricardo Soccol, C.; Tavares, D.; Alberto Zevallos Torres, L.; Oliveira de Andrade Tanobe, V.; Zandoná Filho, A.; Lorenci Woiciechowski, A. Effect of Sequential Acid-Alkaline Treatment on Physical and Chemical Characteristics of Lignin and Cellulose from Pine (*Pinus* spp.) Residual Sawdust. *Bioresour. Technol.* **2020**, *316*, 123884. [CrossRef]
118. Tavares, D.; Cavali, M.; de Oliveira Andrade Tanobe, V.; Alberto Zevallos Torres, L.; Steyner Rozendo, A.; Zandoná Filho, A.; Ricardo Soccol, C.; Lorenci Woiciechowski, A. Lignin from Residual Sawdust of *Eucalyptus* spp.—Isolation, Characterization, and Evaluation of the Antioxidant Properties. *Biomass* **2022**, *2*, 195–208. [CrossRef]
119. National Solid Waste Management Information System Resíduos Dos Serviços de Saneamento Básico. Available online: https://sinir.gov.br/informacoes/tipos-de-residuos/residuos-dos-servicos-de-saneamento-basico/ (accessed on 14 December 2023).
120. Brazilian Association of Public Cleaning and Special Waste Companies. *Panorama Dos Resíduos Sólidos No Brasil*; Brazilian Association of Public Cleaning and Special Waste Companies: São Paulo, Brazil, 2022.
121. Hlaváčiková, H.; Novák, V.; Kameyama, K.; Brezianska, K.; Rodný, M.; Vitková, J. Two Types of Biochars: One Made from Sugarcane Bagasse, Other One Produced from Paper Fiber Sludge and Grain Husks and Their Effects on Water Retention of a Clay, a Loamy Soil and a Silica Sand. *Soil Water Res.* **2019**, *14*, 67–75. [CrossRef]

122. Bhattacharyya, P.; Bisen, J.; Bhaduri, D.; Priyadarsini, S.; Munda, S.; Chakraborti, M.; Adak, T.; Panneerselvam, P.; Mukherjee, A.K.; Swain, S.L.; et al. Turn the Wheel from Waste to Wealth: Economic and Environmental Gain of Sustainable Rice Straw Management Practices over Field Burning in Reference to India. *Sci. Total Environ.* **2021**, *775*, 145896. [CrossRef]
123. Liu, D.; Feng, Z.; Zhu, H.; Yu, L.; Yang, K.; Yu, S.; Zhang, Y.; Guo, W. Effects of Corn Straw Biochar Application on Soybean Growth and Alkaline Soil Properties. *Bioresources* **2020**, *15*, 1463–1481. [CrossRef]
124. Wei, Y.; Li, R.; Lu, N.; Zhang, B. Stabilization of Soil Co-Contaminated with Mercury and Arsenic by Different Types of Biochar. *Sustainability* **2022**, *14*, 13637. [CrossRef]
125. Wang, Z.; Xie, L.; Liu, K.; Wang, J.; Zhu, H.; Song, Q.; Shu, X. Co-Pyrolysis of Sewage Sludge and Cotton Stalks. *Waste Manag.* **2019**, *89*, 430–438. [CrossRef]
126. Adeniyi, A.G.; Ighalo, J.O.; Onifade, D.V. Biochar from the Thermochemical Conversion of Orange (*Citrus sinensis*) Peel and Albedo: Product Quality and Potential Applications. *Chem. Afr.* **2020**, *3*, 439–448. [CrossRef]
127. Rehman, A.; Nawaz, S.; Alghamdi, H.A.; Alrumman, S.; Yan, W.; Nawaz, M.Z. Effects of Manure-Based Biochar on Uptake of Nutrients and Water Holding Capacity of Different Types of Soils. *Case Stud. Chem. Environ. Eng.* **2020**, *2*, 100036. [CrossRef]
128. Sui, F.; Wang, M.; Cui, L.; Quan, G.; Yan, J.; Li, L. Pig Manure Biochar for Contaminated Soil Management: Nutrient Release, Toxic Metal Immobilization, and Chinese Cabbage Cultivation. *Ecotoxicol. Environ. Saf.* **2023**, *257*, 114928. [CrossRef]
129. Dróżdż, D.; Malińska, K.; Wystalska, K.; Meers, E.; Robles-Aguilar, A. The Influence of Poultry Manure-Derived Biochar and Compost on Soil Properties and Plant Biomass Growth. *Materials* **2023**, *16*, 6314. [CrossRef]
130. Sørmo, E.; Silvani, L.; Bjerkli, N.; Hagemann, N.; Zimmerman, A.R.; Hale, S.E.; Hansen, C.B.; Hartnik, T.; Cornelissen, G. Stabilization of PFAS-Contaminated Soil with Activated Biochar. *Sci. Total Environ.* **2021**, *763*, 144034. [CrossRef]
131. Kończak, M.; Siatecka, A.; Nazarkovsky, M.A.; Czech, B.; Oleszczuk, P. Sewage Sludge and Solid Residues from Biogas Production Derived Biochar as an Effective Bio-Waste Adsorbent of Fulvic Acids from Water or Wastewater. *Chemosphere* **2021**, *278*, 130447. [CrossRef]
132. Yan, M.; Zhang, S.; Wibowo, H.; Grisdanurak, N.; Cai, Y.; Zhou, X.; Kanchanatip, E. Antoni Biochar and Pyrolytic Gas Properties from Pyrolysis of Simulated Municipal Solid Waste (SMSW) under Pyrolytic Gas Atmosphere. *Waste Dispos. Sustain. Energy* **2020**, *2*, 37–46. [CrossRef]
133. Scown, C.D.; Baral, N.R.; Yang, M.; Vora, N.; Huntington, T. Technoeconomic Analysis for Biofuels and Bioproducts. *Curr. Opin. Biotechnol.* **2021**, *67*, 58–64. [CrossRef]
134. Campbell, R.M.; Anderson, N.M.; Daugaard, D.E.; Naughton, H.T. Financial Viability of Biofuel and Biochar Production from Forest Biomass in the Face of Market Price Volatility and Uncertainty. *Appl. Energy* **2018**, *230*, 330–343. [CrossRef]
135. Ngabuk, D.A.; Immanuel, J.; Irawati, D.Y. Life Cycle Assessment Kerangka Hand Sanitizer Pedal. *Ind. Syst. Eng. J.* **2022**, *1*, 11–19. [CrossRef]
136. United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development*; United Nations: San Francisco, CA, USA, 2015.
137. Kumar, A.; Bhattacharya, T. Biochar: A Sustainable Solution. *Environ. Dev. Sustain.* **2021**, *23*, 6642–6680. [CrossRef]
138. Gwenzi, W.; Chaukura, N.; Noubactep, C.; Mukome, F.N.D. Biochar-Based Water Treatment Systems as a Potential Low-Cost and Sustainable Technology for Clean Water Provision. *J. Environ. Manag.* **2017**, *197*, 732–749. [CrossRef] [PubMed]
139. Xiang, W.; Zhang, X.; Chen, J.; Zou, W.; He, F.; Hu, X.; Tsang, D.C.W.; Ok, Y.S.; Gao, B. Biochar Technology in Wastewater Treatment: A Critical Review. *Chemosphere* **2020**, *252*, 126539. [CrossRef] [PubMed]
140. Waqas, M.; Aburiazaiza, A.S.; Miandad, R.; Rehan, M.; Barakat, M.A.; Nizami, A.S. Development of Biochar as Fuel and Catalyst in Energy Recovery Technologies. *J. Clean. Prod.* **2018**, *188*, 477–488. [CrossRef]
141. Yousaf, B.; Liu, G.; Abbas, Q.; Wang, R.; Ubaid Ali, M.; Ullah, H.; Liu, R.; Zhou, C. Systematic Investigation on Combustion Characteristics and Emission-Reduction Mechanism of Potentially Toxic Elements in Biomass- and Biochar-Coal Co-Combustion Systems. *Appl. Energy* **2017**, *208*, 142–157. [CrossRef]
142. Aviso, K.; Arogo, J.I.A.; Coronel, A.L.O.; Janairo, C.M.J.; Foo, D.; Tan, R. P-Graph Approach to Planning Biochar-Based Carbon Management Networks. *Chem. Eng. Trans.* **2018**, *70*, 37–42.
143. Rumpel, C.; Amiraslani, F.; Chenu, C.; Garcia Cardenas, M.; Kaonga, M.; Koutika, L.S.; Ladha, J.; Madari, B.; Shirato, Y.; Smith, P.; et al. The 4p1000 Initiative: Opportunities, Limitations and Challenges for Implementing Soil Organic Carbon Sequestration as a Sustainable Development Strategy. *Ambio* **2020**, *49*, 350–360. [CrossRef]