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Review

Overview of Traditional and Contemporary Industrial Production Technologies for Biochar along with Quality Standardization Methods

Mátyás Köves [1], Viktor Madár [2], Marianna Ringer [3,*] and Tamás Kocsis [4]

1 Doctoral School of Horticultural Sciences, Hungarian University of Agriculture and Life Sciences, 1118 Budapest, Hungary; koves.matyas@hallgato.uni-mate.hu
2 Doctoral School of Mechanical Engineering, Hungarian University of Agriculture and Life Sciences, 2100 Gödöllő, Hungary; madar.viktor@pyrowatt.hu
3 Geographical Institute, Research Centre for Astronomy and Earth Sciences, 1118 Budapest, Hungary
4 Institute of Food Science and Technology, Hungarian University of Agriculture and Life Sciences, 1118 Budapest, Hungary; kocsis.tamas.jozsef@uni-mate.hu
* Correspondence: ringer.marianna@csfk.org

Abstract: Biochar refers to any material that has transformed into an amorphous, graphite-like structure as a result of the thermochemical conversion of organic materials. Incorporating biochar into soil contributes to mitigating the effects of climate change through the sequestration and storage of carbon. There are numerous methods for producing biochar, including pyrolysis, gasification, hydrothermal carbonization, and flash carbonization. The choice of technology largely depends on the intended use of the biochar and the type of biomass available. However, traditional production processes often face environmental challenges, especially in developing countries. This study introduces several traditional charcoal-burning techniques used around the world and provides an overview of modern industrial biochar production methods. International organizations have developed standards for determining the quality parameters of biochar and have proposed guidelines for its application in soil. According to the available literature, biochar presents a promising opportunity for advancing sustainable agriculture and mitigating climate change.

Keywords: biochar; charcoal; pyrolysis; standardization; traditional charcoal kilns

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1. Introduction

Biochar is produced by subjecting biomass, such as wood, manure, various wastes, or leaves, to thermal decomposition at relatively low temperatures (<900 °C) in the presence of limited oxygen. Biochar enhances soil fertility primarily by increasing the bioavailability of essential plant nutrients and improving the physical, chemical, and biological properties of soils. Its incorporation into soil modifies the texture, pore size distribution, and bulk density, thereby enhancing aeration and the water retention capacity. Additionally, biochar's high porosity, carbon sequestration potential, and organic matter content contribute to increased soil pH levels, higher water retention, and the improved availability of nitrogen, phosphorus, and various meso- and micronutrients [1].

Biochar has attracted the attention of policymakers due to its promising characteristics that facilitate carbon storage, potentially preventing the release of carbon dioxide into the atmosphere. The Paris Agreement (2015) was a significant step in the fight against climate change, aiming to limit the rise in the global temperature to 2 °C by the end of the century [2]. Studies suggest that current efforts and commitments are insufficient to meet this goal. Negative emission technologies, such as biochar and other carbon removal methods, can play a key role in managing climate change [3].

The interest in agricultural applications of biochar has surged in recent years. Agricultural professionals are increasingly facing the challenges posed by climate change, including extreme weather conditions. Extreme drought and uneven rainfall, which removes organic matter from the soil, prompted producers across most regions to adopt "renewable" water and nutrient retention methods [4]. However, these techniques need not necessarily be referred to as new, as Indigenous Peoples of South America created fertile black soils by enriching charcoal made from biomass nearly 7000 years ago. These so-called "Terra Preta" (Portuguese for black earth) soils have retained their high organic carbon content for thousands of years after their formation [5]. One hectare of Terra Preta soil, one meter deep, contains up to 250 tons of carbon compared to 100 tons in the surrounding soils [6].

Biochar production with modern industrial tools is a well-controlled process, where professionals can keep harmful gas emissions at a low level [7]. However, challenges arise when trying to achieve the same efficiency in tropical, rural conditions, where locals often use outdated technologies, due to the modest financial circumstances in developing countries [8,9]. The biochar industry is globally emerging, with varying production volumes in different regions (Table 1).

Table 1. Estimated annual biochar production of different regions.

Region	Estimated Volume in Metric Tonnes (mt)	Literature
China	300,000–400,000	USBI [10], Xia et al., 2023 [11]
USA	160,000–200,000	USBI [10], Schmidt et al., 2021 [12]
EU	100,000–150,000	IBI [13]
South America	50,000–100,000	USBI [10], IBI [13]
Africa	20,000–50,000	USBI [10], Schmidt et al., 2021 [12]

There are various biochar production methods in different regions, each with its pros and cons in terms of efficiency, gas emissions, and costs (Figure 1). This study aims to delineate traditional charcoal production techniques across diverse global regions and to offer insights into the modern industrial processes for biochar production. Furthermore, this discussion encompasses standardization methods for biochar certification and the legal framework surrounding it.

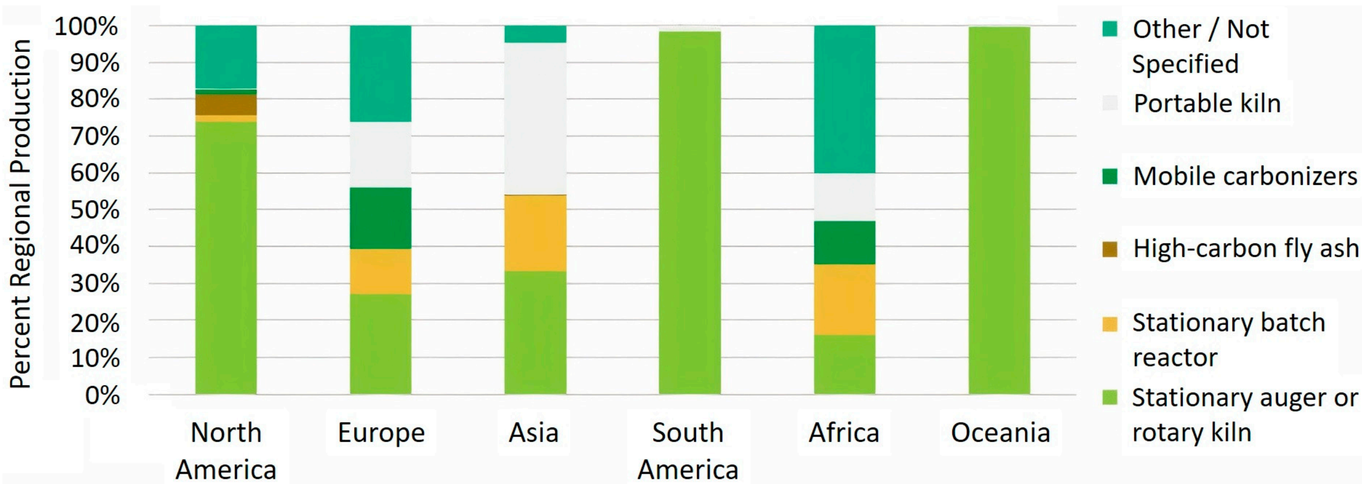

Figure 1. Biochar production by technology type and global region in 2023 [10].

2. Traditional Methods for Producing and Using Charcoal in Different Regions

In the Catalonia region of Spain, so-called "foreigner" (anthill) kilns were traditionally used to dispose of biomass resulting from agricultural or forestry activities, thereby enhancing soil fertility [14]. This technology was prevalent in the region and various other areas of Spain until the 1960s. The formiguers were filled with dry, woody plant waste and then burned under a 10–20 cm thick soil cover. The process, characterized by slow and incomplete combustion, resulted in biochar with an optimal nutrient profile for soil application [15,16], providing essential nutrients such as phosphorus, potassium, and nitrogen [17].

Traditional charcoal manufacturing in Yogyakarta, Indonesia, relies on traditional methods, predominantly earth mound and pit kilns, alongside transportable steel, oil drum, brick, concrete, and fired-clay kilns. The yield from these methods ranges between 22.88% and 35.98% depending on the kiln type, raw material, processing time, and carbonization conditions [18,19]. Traditional charcoal production primarily employs three methods. An earth mound vertically stacked kiln involves stacking wood vertically in an earth-covered mound to control the airflow and promote carbonization. The process yields charcoal with a high volatile matter content but lower fixed carbon content and calorific value. An earth mound horizontally stacked kiln uses wood stacked horizontally. This variation often results in slightly better-quality charcoal compared to the vertical method, with improvements in the fixed carbon content and calorific value. In a pit kiln, wood is covered before burning, leading to a more controlled carbonization process. Charcoal generally exhibits the best quality among the traditional methods, with favorable properties for export markets [20].

In the Southern Province of Rwanda, deforestation and wood scarcity present significant environmental challenges, exacerbated by insufficient strategies and capabilities for sustainable wood energy production and consumption [21]. The traditional kilns used extensively in rural areas do not allow for the efficient conversion of wood to charcoal, resulting in the overuse of wood and, thereby, increasing the pressure on forests. The Food and Agriculture Organization (FAO) has reported that nearly half of the world's charcoal consumption occurs in Africa, where traditional production techniques are prevalent [22–24]. Casamance kilns are widely used, playing a prominent role in reducing the ecological footprint of the area [21]. In contrast to traditional kilns, the design and installation of improved kilns allow for better efficiency and less environmental impact [25,26]. According to Nahayo et al., 2013 [21], the traditional earth mound kiln exhibits a lower yield efficiency, producing charcoal at a mere 7.5% yield. The improved earth mound kiln and the Casamance kiln achieve higher yields of 19% and 20%, respectively.

In Hungary, evidence of charcoal burning dates back to the early 13th century, with a period of significant growth in the 18th and 19th centuries, particularly in the Gemer (Gömör) region (territory of the formal Gemer county located in northern Hungary and southern Slovakia) [24,27]. Traditional pit kilns (called "boksas" in Hungarian) were shallow, plate-shaped pits measuring approximately 3 × 3 m [28]. The pit was established in a carefully prepared area that was leveled and devoid of vegetation. After stacking the wood, it was covered with leaf litter. A layer of dry soil, approximately 2–3 cm thick, was eventually placed on the top. Boksas provided an efficient charcoal yield of approximately 25%.

Charcoal production in **Sweden** dates back to the early Iron Age [29–32] The boreonemoral forests of Sweden exhibit distinct ecological characteristics at the sites of historic charcoal kiln platforms, which are remnants from the 18th to early 20th centuries [33,34].

In Mediterranean forest ecosystems in **Tuscany**, central Italy, the historical practice of charcoal production has had a lasting ecological impact. These platforms are characterized by modified soil properties, transforming them into distinctive microhabitats within the broader forest landscape [29].

In **Wallonia, Belgium**, particularly in the historical agricultural regions, research has been conducted on the long-term impacts of biochar on soil' carbon dynamics, focusing on areas enriched with charcoal remnants from over 150 years ago [35]. This in-depth analysis not only highlights the potential of biochar to improve soil health and carbon sequestration in contemporary agricultural practices but also illustrates the unique historical and geographical contexts of its application [36,37].

Historical traces of traditional charcoal production can be found in other regions of the world, reflecting the types of raw materials and technologies available in these areas (Figure 2) and also serving as evidence of the long-term impact of biochar on soil.

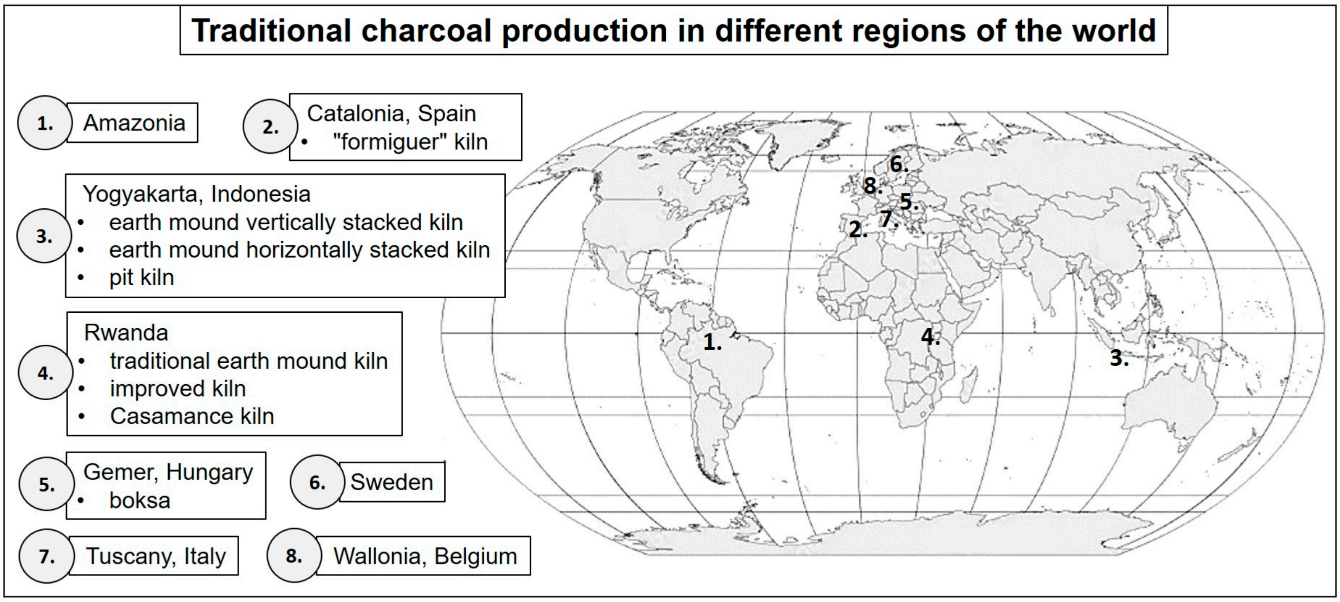

Figure 2. Traditional forms of charcoal production in different regions of the world.

3. Cutting-Edge Techniques for Creating Biochar

Besides the chemical composition of the raw material (biomass), the temperature applied during biochar production plays a key role in shaping the properties of the final product. The pH, porosity, and mineral content significantly depend on the specific production technology [4].

3.1. The Pyrolysis Process and Its Stages

Pyrolysis is a thermal decomposition process that breaks down biomass in an anaerobic environment, with operational temperatures ranging from 300 to 900 °C [38]. This process generates three types of products: solid biochar, a liquid fraction, and gases. During pyrolysis, a series of concurrent and sequential reactions occur, such as dehydration, depolymerization, volatilization, carbonization, aromatization, and others [2,39–41]. The yield and properties of the end products are influenced by the characteristics of the feedstock and the pyrolysis conditions, including the temperature, heating rate, residence time, particle size, and reactor design. The process unfolds in three primary stages: initial moisture removal, core decomposition of biomass constituents, and subsequent secondary reactions that further break down the material. The primary decomposition stage, occurring between 200 and 400 °C, is crucial for the formation of solid char. Specific decomposition ranges for biomass components are well established: hemicellulose between 250 and 350 °C, cellulose from 325 to 400 °C, and the more thermally resilient lignin between 300 and 550 °C [2,40,42].

Low-temperature pyrolysis (500–600 °C) is a prolonged process during which the complete decomposition of cellulose and hemicellulose occurs, leading to the formation of more stabilized biochar [43]. High-temperature pyrolysis (600–1000 °C) is faster and shorter, resulting in more stable but less functional biochar, as cellulose and hemicellulose partially or completely decompose during the process. Pyrolysis technology is diversified into slow, intermediate, fast, and flash types, which are differentiated by their heat transfer rate [2].

Slow pyrolysis, renowned for its high char yield (~20–50%), operates at a slow heating rate within a 400–600 °C temperature window, typically in batch process reactors, retorts, or converters [44,45].

Intermediate pyrolysis, processing at a comparable temperature range but with slow to moderate heating rates, can achieve char yields of ~20–40%. This method utilizes rotary kilns, both externally and internally heated, along with auger-based designs [42,43].

Fast and flash pyrolysis technologies, characterized by rapid heating rates and brief residence times, prioritize bio-oil production, with typical biochar yields of 5–20%. These processes employ reactors like bubbling fluidized beds, circulating fluidized beds, and ablative, cone, and twin-screw reactors designed for mechanical fluidization [45–47].

Moreover, emerging pyrolysis methodologies, including microwave-assisted, vacuum-assisted, and hydropyrolysis, present alternative strategies for biomass conversion [46]. Among these, slow and intermediate pyrolysis technologies are particularly effective for biochar production, with continuous rotary kilns and auger-based kilns representing robust and established solutions [44,45].

3.2. Gasification and Hydrothermal Carbonization

Gasification stands out as a specialized thermochemical transformation that results in 85% syngas, 10% oil, and 5% biochar [48,49]. During the process, the biomass is exposed to a controlled amount of oxygen, air, or steam, leading to the breakdown of its organic components into simpler gases, primarily hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2). This process may also produce small amounts of methane (CH_4) and other trace gases. Syngas, with its rich composition of H_2 and CO, is a versatile energy carrier and feedstock for various industrial applications [50,51].

Hydrothermal carbonization (HTC) is a thermochemical process that transforms biomass into char within a water-based, inert environment, applying high pressure and extending the residence time from several hours to days. This technology is distinguished by its ability to operate at both low (below 300 °C) and high (300–800 °C) temperatures [52–54]. Notably, HTC achieves significant char yields, with low-temperature processes yielding around 65% and high-temperature processes between 30 and 60% [50]. A key advantage of HTC lies in its capacity to process moist biomass without the need for drying, presenting a distinct benefit over other technologies. While HTC is efficient in producing high yields of biochar, the biochar's physicochemical characteristics can vary markedly from those obtained through slow pyrolysis. Despite its high efficiency, the European biochar certificate does not classify HTC-derived chars as biochar [55], suggesting a distinction in their applicability and environmental impact. However, HTC might be more advantageous for generating biocarbon aimed at energy production, as the chars produced have a low ash content and high calorific value [2,55].

Flash carbonization is an innovative thermochemical methodology that includes the initiation and regulation of swift combustion within a densely packed bed of biomass under high pressure. This process is characterized by a unique interaction where the fire ascends through the biomass while air is concurrently drawn downward, facilitating the transformation of lignocellulosic biomass primarily into gas and solid by-products. Typically, the process is completed in less than 30 min, maintaining temperatures ranging from 330 to 650 °C [56–59]. The efficiency of flash carbonization in producing biochar is approximately 28 to 32%. However, a notable challenge of this technique is the necessity for maintaining a high-pressure environment [50,57].

Each of these techniques produces biochar with varying proportions and properties (Figure 3). The selection of suitable technology is contingent upon the particular application objectives of the biochar and the type of biomass that is accessible [1].

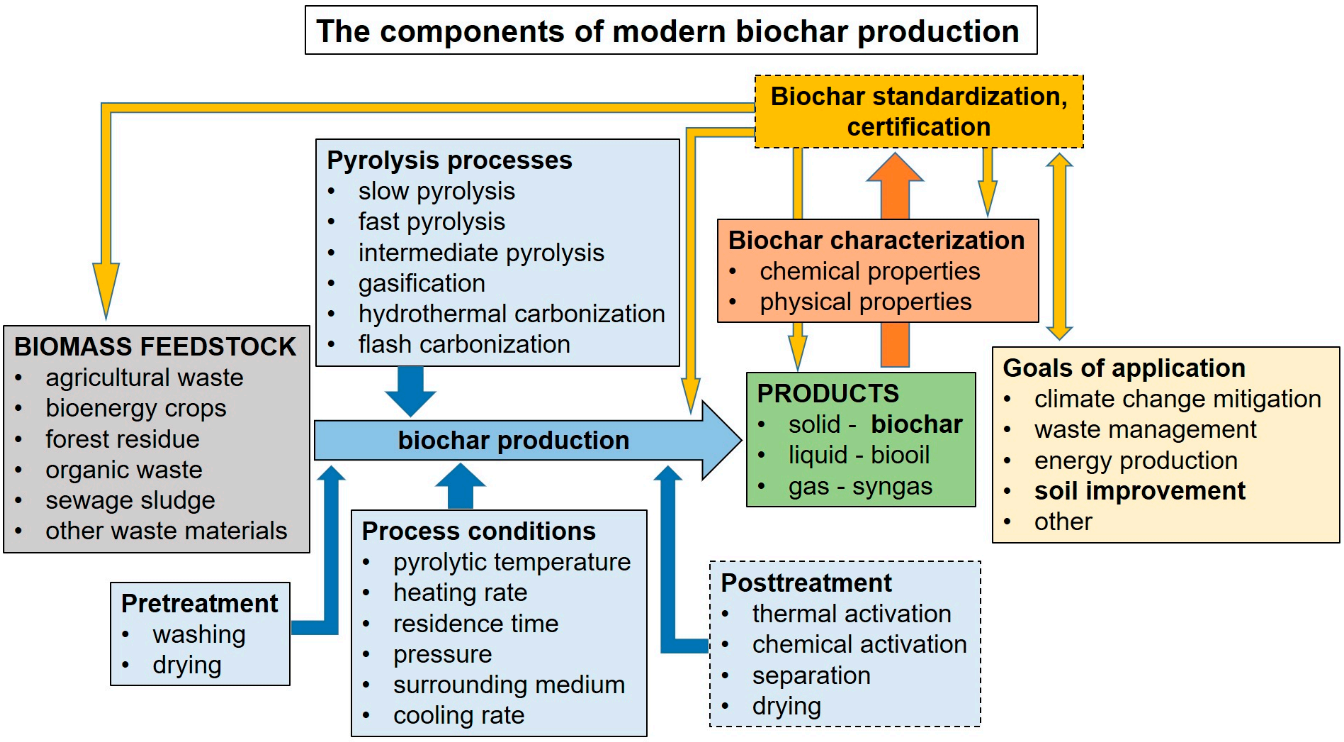

Figure 3. The components of modern biochar production.

4. Standardization of Biochar

Due to the variability of biochar and the heterogeneity in soil properties across spatial and temporal scales, a sustainable utilization strategy is required, comprehensively addressing spatial heterogeneity and encompassing field-to-regional scales, within the relevant socio-economic framework. This context includes considerations of the feedstock availability, resource competition, land use, agricultural practices, and greenhouse gas (GHG) emissions. Transparent procedures and processes are essential to achieve the sustainable production and application of biochar (Figure 4). The certification of biochar is identified as a feasible approach, acting as an essential tactic in the implementation of sustainability policies. The structure of the certification scheme, whether it functions as a standalone approach or a subsystem incorporating various methodologies such as life cycle assessment (LCA), zero-waste strategies, or contamination control measures, plays a pivotal role in its effectiveness [60,61].

Certification schemes exhibit a broad spectrum, ranging from voluntary to mandatory, self-regulated to externally audited, encompassing simple classifications to comprehensive life cycle assessments, and from single-issue focus to multi-issue integration [61]. The establishment of sustainable biochar systems requires a dual approach, incorporating both "sustainable production" and "sustainable application" [55,61].

Certification typically communicates to consumers through stamps or eco-labels upon verification that the product meets specified criteria. The extension of biochar labeling is required, including both the technical description of biomass feedstock and biochar material and the environmental and socio-economic contexts relevant to the application site and feedstock origin [62]. An ideal labeling system would offer environmental data on predetermined parameters through life cycle assessment, which would be verified by an impartial third party [61].

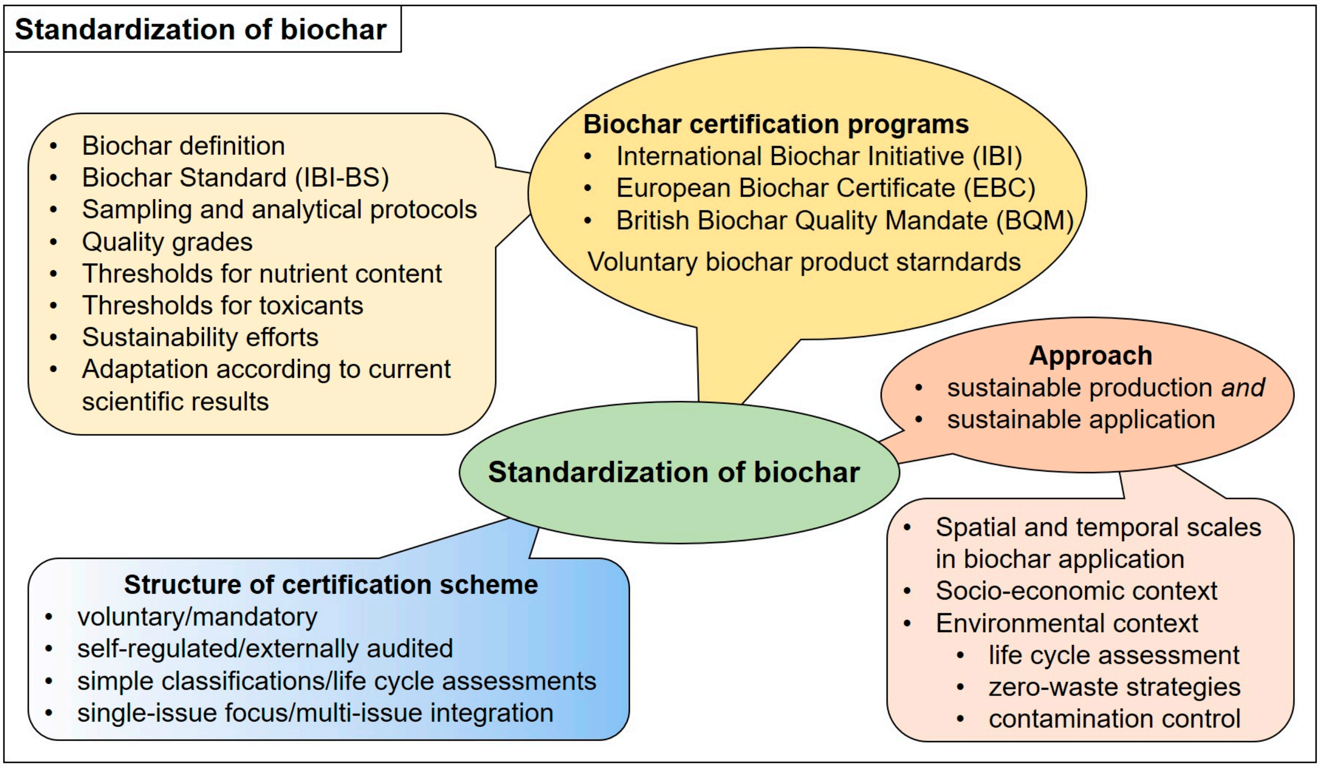

Figure 4. Standardization of biochar.

Given the nascent stage of employing carbonized biomass within agricultural sectors for soil enhancement and climate change mitigation (specifically biochar), both national and supranational regulatory frameworks within the European Union have not yet been fully developed to oversee the production and application of biochar. This deficiency is conveyed by the absence of the term "biochar" in any existing European or national legislation [13,63]. Nonetheless, the efforts by biochar producers and users resulted in partial success in integrating biochar products within the existing legislative frameworks for fertilizers, soil improvers, and composts in various EU countries [63].

Voluntary biochar product standards: Voluntary biochar product standards serve a crucial role in ensuring the sustainability and quality of various products. These standards empower consumers to make informed choices by distinguishing products based on their adherence to sustainability criteria [64]. The adoption of voluntary standards in regulatory contexts underscores the evolving relationship between voluntary certification initiatives and formal legislative requirements, enhancing the transparency and accountability of product sustainability claims [62].

Currently, three emerging biochar certification programs and standards are recognized: (1) the International Biochar Initiative (IBI), 2013; (2) the European Biochar Certificate (EBC), 2012; and (3) the British Biochar Quality Mandate (BBF), 2013. These frameworks share the objectives of ensuring quality and safety for biochar products as soil amendments and fostering the growth of the biochar industry and commercialization. Moreover, they provide foundational information for future regulatory or legislative frameworks while ensuring compliance with relevant environmental quality criteria.

The International Biochar Initiative (IBI), functioning as a non-profit entity headquartered in the United States, concentrates its efforts on advocating for best practices within the industry, facilitating collaboration among stakeholders, and upholding stringent environmental and ethical guidelines. Its aims include the development of biochar systems that are both economically viable and environmentally sustainable. In the year 2015, the IBI unveiled version 2.1 of its Biochar Standard (IBI-BS) [13], featuring comprehensive product definitions and testing protocols specifically tailored for biochar as a soil amendment [63,65].

A crucial requirement of the IBI-BS is that biochar products must possess a minimum organic carbon content of 10%. Additionally, these products are mandated to exhibit a hydrogen-to-organic carbon ratio below 0.7 as an indicator of biochar stability. The standard necessitates the disclosure of various product attributes, including, but not limited to, the moisture content, total ash content, total nitrogen content, pH value, and electrical conductivity (as an indicator of salinity), as well as the CaCO3 content and particle size distribution. The IBI-BS imposes thresholds for potential toxic elements (PTEs) and specific organic pollutants, including polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polychlorinated dibenzodioxins (PCDDs), and polychlorinated dibenzofurans (PCDFs). To ensure no adversely affected seed growth, biochar is also required to pass a germination inhibition assay [13,63,65].

The IBI-BS outlines precise sampling and analytical protocols, with the testing frequency dependent on the feedstock type and production method. Biochar from biomass-fueled combustion must undergo quarterly pollutant tests. Producers are required to document feedstock data thoroughly, including the chain of custody and test results [2,13]. Compliance with the IBI-BS is verified by reviewing documents submitted by manufacturers and testing laboratories. The standard does not require on-site checks or independent verification by government-certified bodies. It excludes hazardous municipal solid waste from feedstock but does not demand sustainability criteria or specific practices for biochar production, such as GHG emission evaluations [13,66].

The European Biochar Certificate (EBC) marked an advancement for biochar within the European Union (EU), where biochar was previously unrecognized in legal statutes. The EBC was developed to precisely define biochar, enabling its assimilation into existing legal frameworks concerning fertilizers and soil ordinances by establishing biochar as a quality-manufactured product rather than waste. EBC was crucial for adopting a transparent production and analysis control system for biochar, linked to the nuances of production technology and feedstock types [67].

The objectives of EBC encompass multiple domains: establishing a control mechanism grounded in cutting-edge scientific research and methodologies; furnishing consumers with a reliable quality standard; allowing producers to validate their adherence to rigorous quality criteria; promoting the dissemination of current knowledge to guide future regulatory frameworks; and pre-emptively addressing potential hazards linked with biochar utilization [63].

The supervision of adherence to the EBC standards is administered by q.inspecta, an autonomous quality assurance entity recognized by governmental authorities. This oversight spans throughout Europe, with annual on-site audits performed by regional inspection agencies. Biochar producers generating less than 50 tons per annum are exempt from these on-site inspections; however, are obligated to adhere to a structured framework of self-disclosure and comprehensive process documentation [55].

Laboratories assessing biochar must adhere to the EBC's analytical methods, as specified in the guidelines set forth by the European Biochar Foundation (2012) and detailed by Bachmann [67]. Laboratories are required to validate their compliance through participation in ring trials or inter-laboratory comparisons. The focus is on elemental analysis, including C, H, N, O, and S. Other areas of focus include the ash content, major elements, heavy metals, and organic contaminants. The organic contaminants assessed are polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polychlorinated dibenzodioxins (PCDDs), and polychlorinated dibenzofurans (PCDFs). Additional measurements include the pH, electrical conductivity (EC), and specific surface area.

EBC distinguishes between "basic" and "premium" biochar grades, each defined by unique threshold values for heavy metals and organic pollutants. The "basic" grade conforms to the German Federal Soil Protection Act, while the "premium" grade adheres to the more stringent Swiss Chemical Risk Reduction Act of 2005. EBC framework outlines permissible biomass feedstocks for biochar production and establishes comprehensive sustainability metrics, including emissions, energy efficiency, heat recovery, feedstocks procurement policies (emphasizing a maximum transport distance of 80 km to the pyrolysis plant), and guidelines for biochar storage, fire and dust protection, handling, and labeling [68].

The British Biochar Quality Mandate (BQM), launched in 2011 with support from the Esmée Fairbairn Foundation and officially authorized by the British Biochar Foundation (BBF) in 2013, represents a UK-specific initiative aimed at standardizing biochar quality. This voluntary scheme, which culminated in the release of its first version in July 2014, was developed collaboratively by scientists, policymakers, and regulators. It mirrors the approach of creating official guidance documents for classifying waste-derived materials as non-waste, achieving "end of waste" status, and has produced 14 Quality Protocols for various materials [69].

BQM sets out Maximum Permissible Limits (MPLs) for toxicants and delineates key biochar properties like the water holding capacity and cation exchange capacity, aiming for a dual-tiered quality grading system (standard and high grade) with distinct criteria for each. This system is grounded in sustainability evaluations of feedstocks, incorporating the chain of custody and evidence of legal and sustainable management alongside life cycle assessment methodologies for GHG savings. It leverages existing UK and EU legislation, enhanced with specific emission standards for biochar production while setting guidelines for biochar application to safeguard human health and ensure environmental integrity [63,69].

Despite the current absence of commercially accredited products under the BQM, plans are in place to update and extend the mandate to reflect new EU developments and applications of biochar [63,69].

5. Conclusions

The examination of biochar's traditional sources and contemporary production methods, in conjunction with its standardization and regulatory context, highlights its potential as a means for environmental conservation and agricultural advancement. Integrating historical land management practices with current environmental strategies provides vital insights into sustainable agricultural techniques that can significantly enhance soil fertility and contribute to global climate mitigation efforts. To advance the biochar industry, policymakers should provide financial incentives and fund R&D for process and application improvements. Supporting education and training, facilitating market development, and encouraging sustainable practices are essential. Collaboration among stakeholders and robust impact monitoring will further optimize the benefits and drive industry growth. Implementing these measures can enhance biochar's role in environmental management and agricultural productivity.

The development and adoption of rigorous standards, alongside certifications spearheaded by initiatives like the IBI, EBC, and BQM, play a crucial role in ensuring the integrity, safety, and environmental efficacy of biochar in developed countries. These frameworks not only guarantee the quality of biochar products but also foster trust among consumers, producers, and policymakers, thereby facilitating the growth of the biochar industry.

In developing countries, traditional charcoal production methods—adapted to local conditions—form the main basis for today's biochar production. Facing technological and financial barriers along with environmental issues, biochar production and application are typically carried out and regulated on a local scale.

Building a sustainable biochar application system requires extensive scientific knowledge of biochar–soil interactions and the consideration of relevant socio-economic and temporal factors. The study of the soils in areas used for charcoal production over the centuries provides an opportunity to reveal the long-term effects of biochar on soil. Historical charcoal production practices, like those in Catalonia and Hungary, have left lasting impacts on the soil structure. Additionally, biochar's stability contributes to long-term carbon sequestration, mitigating the effects of climate change by storing carbon in the soil for centuries. In regions such as Wallonia and Tuscany, historical charcoal production has altered the soil properties to create distinctive microhabitats. This effect demonstrates biochar's role in improving soil health and enhancing biodiversity by modifying soil conditions and creating stable, long-term environments for various organisms.

Adaptive regulation that accommodates new knowledge and development is essential, potentially requiring regular revisions and updates.

As the biochar sector evolves, the emphasis should persistently be on enhancing production methodologies, broadening research partnerships, and fine-tuning regulatory structures. Prospects for biochar involve advancements in pyrolysis technology and feedstock optimization to enhance the yield, quality, and cost effectiveness. Emerging methods like microwave-assisted and hydrothermal carbonization could expand biochar's applications. Research may lead to tailored biochar formulations for various crops and soils. Additionally, biochar could integrate with waste management practices, converting waste into valuable soil amendments, and with other technologies such as composting and precision agriculture to further improve soil health and productivity. Such efforts will ensure that biochar can fully realize its potential as a cornerstone of sustainable agricultural practices and a powerful tool in the fight against climate change.

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References

1. Kocsis, T.; Ringer, M.; Biró, B. Characteristics and applications of biochar in soil-plant systems: A short review of benefits and potential drawbacks. *Appl. Sci.* **2022**, *12*, 4051. [CrossRef]
2. Spash, C.L. This changes nothing: The Paris Agreement to ignore reality. *Globalizations* **2016**, *13*, 928–933. [CrossRef]
3. Fawzy, S.; Osman, A.; Yang, H.; Doran, J.; Rooney, D.W. Industrial biochar systems for atmospheric carbon removal: A review. *Environ. Chem. Lett.* **2021**, *19*, 3023–3055. [CrossRef]
4. Novotny, E.; Maia, C.; Carvalho, M.; Madari, B.E. Biochar: Pyrogenic carbon for agricultural use—A critical review. *Rev. Bras. CiÊNcia Do Solo* **2015**, *39*, 321–344. [CrossRef]
5. Factura, H.; Bettendorf, T.; Buzie, C.; Pieplow, H.; Reckin, J.; Otterpohl, R. Terra Preta sanitation: Re-discovered from an ancient Amazonian civilization—Integrating sanitation, bio-waste management and agriculture. *Water Sci. Technol.* **2010**, *61*, 2673–2679. [CrossRef] [PubMed]
6. Glaser, B. Prehistorically modified soils of central Amazonia: A model for sustainable agriculture in the twenty-first century. *Philos. Trans. R. Soc. Biol. Sci.* **2007**, *362*, 187–196. [CrossRef] [PubMed]
7. Bacskai, I.; Madar, V.; Fogarassy, C.; Toth, L. Modeling of Some Operating Parameters Required for the Development of Fixed Bed Small Scale Pyrolysis Plant. *Resources* **2019**, *8*, 79. [CrossRef]
8. Peters, J.F.; Iribarren, D.; Dufour, J. Biomass pyrolysis for biochar or energy applications? A life cycle assessment. *Environ. Sci. Technol.* **2015**, *49*, 5195–5202. [CrossRef] [PubMed]
9. Kampa, M.; Castanas, E. Human health effects of air pollution. *Environ. Pollut.* **2008**, *151*, 362–367. [CrossRef] [PubMed]
10. USBI—2023 Global Biochar Market Report. *Int. Biochar Initiat*. Available online: https://biochar-international.org/2023-global-biochar-market-report/ (accessed on 22 August 2014).
11. Xia, L.; Chen, W.; Lu, B.; Wang, S.; Xiao, L.; Liu, B.; Yang, H.; Huang, C.; Wang, H.; Yang, Y.; et al. Climate mitigation potential of sustainable biochar production in China. *Renew. Sustain. Energy Rev.* **2023**, *175*, 113145. [CrossRef]
12. Schmidt, H.P.; Kammann, C.; Hagemann, N.; Leifeld, J.; Bucheli, T.D.; Sánchez Monedero, M.A.; Cayuela, M.L. Biochar in agriculture—A systematic review of 26 global meta-analyses. *GCB Bioenergy* **2021**, *13*, 1708–1730. [CrossRef]
13. IBI—International Biochar Initiative. Standardized Product Definition and Product Testing Guidelines for Biochar that is Used in Soil: Version Number 2.1. Available online: https://biochar-international.org/wp-content/uploads/2020/06/IBI_Biochar_Standards_V2.1_Final2.pdf (accessed on 22 August 2014).

14. Lashof, D.A.; Ahuja, D.R. Relative contributions of greenhouse gas emissions to global warming. *Nature* **1990**, *344*, 529–531. [CrossRef]
15. Olarieta, J.R.; Padrò, R.; Masip, G.; Rodríguez-Ochoa, R.; Tello, E. 'Formiguers', a historical system of soil fertilization (and biochar production?). *Agric. Ecosyst. Environ.* **2011**, *140*, 27–33. [CrossRef]
16. Miret, J. Las rozas en la Península Ibérica. Apuntes de tecnología agyar n tradicional. *Hist. Agrar.* **2004**, *34*, 165–193.
17. Marks, E.A.; Mattana, S.; Alcañiz, J.M.; Pérez-Herrero, E.; Domene, X. Gasifier biochar effects on nutrient availability, organic matter mineralization, and soil fauna activity in a multi-year Mediterranean trial. *Agric. Ecosyst. Environ.* **2016**, *215*, 30–39. [CrossRef]
18. Smith, K.R.; Pennise, D.M.; Khummongkol, P.; Zhang, J.; Panyathanya, W.; Rasmunsen, R.A.; Khalil, M.A.K. *Greenhouse Gases from Small Scale Combustion Devices in Developing Countries: Phase III: Charcoal Kiln in Thailand*; Summary of Complete Report for USEPA; U.S. Environmental Protection Agency: Washington, DC, USA, 1999.
19. Pratiwi, Y.; Waluyo, J.; Widyawidura, W.; Aridito, M.N. Development of Jackfruit Peel Waste as Biomass Energy: Case study for traditional food center in Yogyakarta. *Int. J. Renew. Energy Res.* **2019**, *9*, 2138–2135.
20. Sulistyo, J.; Marsoem, S.N.; Kholik, A.; Lukmandaru, G. Traditional charcoal manufacturing methods and its quality in Yogyakarta. In Proceedings of the Seminar Nasional MAPEKI IV, Samarinda, Indonesia, 6–9 August 2002; pp. 6–9.
21. Nahayo, A.; Ekise, I.; Mukarugwiza, A. Comparative Study on Charcoal Yield Produced by Traditional and Improved Kilns: A Case Study of Nyaruguru and Nyamagabe Districts in Southern Province of Rwanda. *Energy Environ. Res.* **2013**, *3*, 40. [CrossRef]
22. Kammen, D.M.; Lew, D.J. *Review of Technologies for the Production and Use of Charcoal*; Renewable and Appropriate Energy Laboratory Report; Renewable & Appropriate Energy Laboratory: Berkeley, UC, USA, 2005.
23. Kokou, K.; Nuto, Y.; Atsri, H. Impact of charcoal production on woody plant species in West Africa: A case study in Togo. *Sci. Res. Essays* **2009**, *4*, 881–893.
24. Veres, G. A bükki faszénégetés a 20. század utolsó évtizedében. Kelet-KözÉP-EurÓPai TörtÉNelmi TanulmÁNyok/East Cent. *Eur. Hist. Stud.* **2022**, *49*, 235–247.
25. Mencarelli, A.; Cavalli, R.; Greco, R.; Grigolato, S. Comparison of Technical and Operational Conditions of Traditional and Modern Charcoal Kilns: A Case Study in Italy. *Energies* **2023**, *16*, 7757. [CrossRef]
26. Ighalo, J.O.; Eletta, O.A.; Adeniyi, A.G. Biomass carbonisation in retort kilns: Process techniques, product quality and future perspectives. *Bioresour. Technol. Rep.* **2022**, *17*, 100934. [CrossRef]
27. Kocsis, T.; Biró, B.; Ulmer, Á.; Szántó, M.; Kotroczó, Z. Time-lapse effect of ancient plant coal biochar on some soil agrochemical parameters and soil characteristics. *Environ. Sci. Pollut. Res.* **2018**, *25*, 990–999. [CrossRef] [PubMed]
28. Gömöri, J. *Az Avar Kori és Árpád-Kori Vaskohászat Régészeti Emlékei Pannóniában—The Archeometallurgical Sites in Pannonia from the Avar and Early Árpád-Period (Register of Industrial Archelogical Sites in Hungary 1. Ironworking)*; Archaeological Collection of the Museum of Sopron: Sopron, Hungary, 2000.
29. Carrari, E.; Ampoorter, E.; Verheyen, K.; Coppi, A.; Selvi, F. Former charcoal kiln platforms as microhabitats affecting understorey vegetation in Mediterranean forests. *Appl. Veg. Sci.* **2016**, *19*, 486–497. [CrossRef]
30. Hardy, B.; Cornelis, J.; Houben, D.; Leifeld, J.; Lambert, R.; Dufey, J. Evaluation of the long-term effect of biochar on properties of temperate agricultural soil at pre-industrial charcoal kiln sites in Wallonia, Belgium. *Eur. J. Soil Sci.* **2017**, *68*, 80–89. [CrossRef]
31. Hirsch, F.; Raab, T.; Ouimet, W.; Dethier, D.; Schneider, A.; Raab, A. Soils on Historic Charcoal Hearths: Terminology and Chemical Properties. *Soil Sci. Soc. Am. J.* **2017**, *81*, 1427–1435. [CrossRef]
32. Hirsch, F.; Schneider, A.; Bauriegel, A.; Raab, A.; Raab, T. Formation, Classification, and Properties of Soils at Two Relict Charcoal Hearth Sites in Brandenburg, Germany. *Front. Environ. Sci.* **2018**, *6*, 94. [CrossRef]
33. Ellis, E.C.; Ramankutty, N. Putting people on the map: Anthropogenic biomes of the world. *Front. Ecol. Environ.* **2008**, *6*, 439–447. [CrossRef]
34. Eriksson, O.; Lundin, L. Legacies of historic charcoal production affect the forest flora in a Swedish mining district. *Nord. J. Bot.* **2021**, *39*, 11. [CrossRef]
35. Hernandez-Soriano, M.; Bart, K.; Goos, P.; Hardy, B.; Dufey, J.; Smolders, E. Long-term effect of biochar on the stabilization of recent carbon: Soils with historical inputs of charcoal. *Bioenergy* **2015**, *8*, 371–381. [CrossRef]
36. Liang, B.; Lehmann, J.; Sohi, S.P. Black carbon affects the cycling of nonblack carbon in soil. *Org. Geochem.* **2010**, *41*, 206–213. [CrossRef]
37. Major, J.; Rondon, M.; Molina, D.; Riha, S.; Lehmann, J. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant Soil* **2010**, *333*, 117–128. [CrossRef]
38. Lehmann, J.; Joseph, S. *Biochar for Environmental Management: Science, Technology and Implementation*, 3rd ed.; Routledge: London, UK, 2024; p. 884.
39. Demirbas, A. Pyrolysis mechanisms of biomass materials. *Energy Sources A* **2009**, *31*, 1186–1193. [CrossRef]
40. Kan, T.; Strezov, V.; Evans, T.J. Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. *Renew. Sustain. Energy Rev.* **2016**, *57*, 1126–1140. [CrossRef]
41. Uddin, M.N.; Techato, K.; Taweekun, J.; Rahman, M.M.; Rasul, M.G.; Mahlia, T.M.I.; Ashrafur, S.M. An overview of recent developments in biomass pyrolysis technologies. *Energies* **2018**, *11*, 3115. [CrossRef]
42. Osman, A.I.; Young, T.J.; Farrell, C.; Harrison, J.; Al-Muhtaseb, A.A.H.; Rooney, D.W. Physicochemical characterization and kinetic modeling concerning combustion of waste berry pomace. *CS Sustain. Chem. Eng.* **2020**, *8*, 17573–17586. [CrossRef]

43. Chen, W.H.; Kuo, P.C. Isothermal torrefaction kinetics of hemicellulose, cellulose, lignin and xylan using thermogravimetric analysis. *Energy* **2011**, *36*, 6451–6460. [CrossRef]
44. Hornung, A. Biomass pyrolysis. In *Encyclopedia of Sustainability Science and Technology*; Meyers, R.A., Ed.; Springer: New York, NY, USA, 2012; pp. 1517–1531.
45. Brassard, P.; Godbout, S.; Raghavan, V. Pyrolysis in auger reactors for biochar and bio-oil production: A review. *Biosyst. Eng.* **2017**, *161*, 80–92. [CrossRef]
46. Yang, Y.; Brammer, J.G.; Mahmood, A.S.N.; Hornung, A. Intermediate pyrolysis of biomass energy pellets for producing sustainable liquid, gaseous and solid fuels. *Bioresour. Technol.* **2014**, *169*, 794–799. [CrossRef]
47. Waluyo, J.; Makertihartha, B.N.; Susanto, H. Pyrolysis with intermediate heating rate of palm kernel shells: Effect temperature and catalyst on product distribution. *AIP Conf. Proc.* **2018**, *1977*, 020026.
48. Tripathi, M.; Sahu, J.N.; Ganesan, P. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renew. Sustain. Energy Rev.* **2016**, *55*, 467–481. [CrossRef]
49. Tisserant, A.; Cherubini, F. Potentials, limitations, co-benefits, and trade-offs of biochar applications to soils for climate change mitigation. *Land* **2019**, *8*, 179. [CrossRef]
50. Kumar, A.; Saini, K.; Bhaskar, T. Advances in design strategies for preparation of biochar based catalytic system for production of highvalue chemicals. *Bioresour. Technol.* **2020**, *299*, 122564. [CrossRef] [PubMed]
51. Wang, D.; Jiang, P.; Zhang, H.; Yuan, W. Biochar production and applications in agro and forestry systems: A review. *Sci. Total Environ.* **2020**, *723*, 137775. [CrossRef] [PubMed]
52. Malghani, S.; Gleixner, G.; Trumbore, S.E. Chars produced by slow pyrolysis and hydrothermal carbonization vary in carbon sequestration potential and greenhouse gases emissions. *Soil Biol. Biochem.* **2013**, *62*, 137–146. [CrossRef]
53. Sharma, R.; Jasrotia, K.; Singh, N.; Ghosh, P.; Srivastava, S.; Sharma, N.R.; Kumar, A. A comprehensive review on hydrothermal carbonization of biomass and its applications. *Chem. Afr.* **2020**, *3*, 1–19. [CrossRef]
54. Afolabi, O.O.; Sohail, M.; Cheng, Y.L. Optimisation and characterisation of hydrochar production from spent coffee grounds by hydrothermal carbonisation. *Renew. Energy* **2020**, *147*, 1380–1391. [CrossRef]
55. EBC—European Biochar Certificate—(2012) European Biochar Certificate—Guidelines for a Sustainable Production of Biochar. European Biochar Foundation (EBC), Arbaz, Switzerland. Available online: http://European-biochar.org (accessed on 2 December 2020).
56. Antal, M.; Grønli, M. The art, science, and technology of charcoal production. *Ind. Eng. Chem. Res.* **2003**, *42*, 1619–1640. [CrossRef]
57. Nunoura, T.; Wade, S.R.; Bourke, J.P.; Antal, M.J. Studies of the flash carbonization process. 1. Propagation of the flaming pyrolysis reaction and performance of a catalytic afterburner. *Ind. Eng. Chem. Res.* **2006**, *45*, 585–599. [CrossRef]
58. Nartey, O.; Zhao, B. Biochar preparation, characterization, and adsorptive capacity and its effect on bioavailability of contaminants: An overview. *Adv. Mater. Sci. Eng.* **2014**, *2014*, 715398. [CrossRef]
59. Hirst, E.A.; Taylor, A.; Mokaya, R. A simple flash carbonization route for conversion of biomass to porous carbons with high CO_2 storage capacity. *J. Mater. Chem. A* **2018**, *6*, 12393–12403. [CrossRef]
60. Cobut, A.; Beauregard, R.; Blanchet, P. Using life cycle thinking to analyse environmental labeling: The case of appearance wood products. *Int. J. Life Cycle Assess.* **2013**, *18*, 722–742. [CrossRef]
61. Verheijen, F.G.; Bastos, A.C.; Schmidt, H.P.; Brandão, M.; Jeffery, S. Biochar sustainability and certification. In *Biochar for Environmental Management*; Routledge: London, UK, 2015; pp. 795–812.
62. Verheijen, F.G.; Bastos, A.C.; Schmidt, H.P.; Jeffery, S. Biochar and certification 1. In *Sustainability Certification Schemes in the Agricultural and Natural Resource Sectors*; Routledge: London, UK, 2019; pp. 113–136.
63. Meyer, S.; Genesio, L.; Vogel, I.; Schmidt, H.-P.; Soja, G.; Someus, E.; Shackley, S.; Verheijen, F.G.A.; Glaser, B. Biochar standardization and legislation harmonization. *J. Environ. Eng. Landsc. Manag.* **2017**, *25*, 175–191. [CrossRef]
64. He, M.; Xu, Z.; Hou, D.; Gao, B.; Cao, X.; Ok, Y.S.; Tsang, D.C. Waste-derived biochar for water pollution control and sustainable development. *Nat. Rev. Earth Environ.* **2022**, *3*, 444–460. [CrossRef]
65. Schmidt, H.-P.; Shackley, S. Science and practice: Biochar horizon 2025. In *Biochar in European Soils and Agriculture*; Routledge: London, UK, 2016.
66. Scarlat, N.; Dallemand, J.F. Recent developments of biofuels/bioenergy sustainability certification: A global overview. *Energy Policy* **2011**, *39*, 1630–1646. [CrossRef]
67. Bachmann, H.J.; Bucheli, T.D.; Dieguez-Alonso, A.; Fabbri, D.; Knicker, H.; Schmidt, H.P.; Zehetner, F. Toward the standardization of biochar analysis: The COST action TD1107 interlaboratory comparison. *J. Agric. Food Chem.* **2016**, *64*, 513–527. [CrossRef]
68. Renckens, S. *Private Governance and Public Authority: Regulating Sustainability in a Global Economy*; Cambridge University Press: Cambridge, UK, 2020; p. 306.
69. Shackley, S.; Esteinou, R.I.; Hopkins, D.; Hammond, J. *Biochar Quality Mandate (BQM) Version 1.0.*; British Biochar Foundation: Edinburgh, UK, 2014; p. 55.