Review

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Omotayo E. Ojewumi * , Gang Chen , Modupe E. Ojewumi

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Biochar Production: Toward Safe, Effective, and Sustainable Agriculture

Omotayo E. Ojewumi *, Gang Chen and Modupe E. Ojewumi

Department of Civil and Environmental Engineering, Florida Agricultural & Mechanical University-Florida State University College of Engineering, Tallahassee, FL 32310, USA

* Correspondence: omotayo1.ojewumi@famu.edu

Abstract

Biochar, a carbon-rich product resulting from the thermochemical transformation of organic biomass feedstocks in the absence or limited availability of oxygen, is currently drawing much worldwide attention due to its multiple applications in carbon sequestration, soil improvement, environmental remediation, and biomass waste management. Initially, the focus of research was primarily on the technical possibilities of biochar production, its economic aspects, and its contribution to climate change mitigation through carbon sequestration and the promotion of sustainable agriculture. Nevertheless, recent research indicates the high complexity and dynamics of biochar interactions with the environment, driven by a combination of feedstock type, process conditions, biochar properties, and other factors. While biochar exhibits multiple positive effects, including improving soil structure, enhancing nutrient retention, promoting microbial activities, and remediating contaminants, several environmental risks associated with biochar application have also been identified, namely the formation of polycyclic aromatic hydrocarbons (PAHs), heavy metal contamination, creation of persistent free radicals, changes in soil chemistry, and modification of soil microbial community structure. Such risks are greatly related to production process parameters, treatment methods, and biochar application practices. Moreover, differences in feedstock choice, pyrolysis temperature, reactor design, biochar application rate, and analytical methods used make comparative analysis of results difficult.

Keywords: Biochar; pyrolysis; soil amendment; soil remediation; contaminant dynamics; soil health; environmental risk assessment

1. Introduction

Biochar is a carbonaceous substance that is formed via the pyrolysis of biomass. Early investigations concluded that biochar is technically and economically viable and contributes to greenhouse gas reduction. Such results promoted the application of biochar in sustainable agriculture and environmental management [1,2]. At the beginning, the main advantages of using biochar were considered to lie in its carbon stability, which would improve the quality of degraded soil and, therefore, increase agricultural yields [3]. Later research showed that biochar behavior in soil was more complex, and its efficiency depended on many factors [4]. Properties and functioning of biochar depend on pyrolysis temperatures, the nature of biomass, and reactors used in their production [5,6]. Moreover, biochar's functionality is significantly affected by environmental and soil conditions [5].

On the other hand, concerns have been raised about the safety of using biochar for agricultural purposes due to its environmental impacts. These problems include the creation and accumulation of polycyclic aromatic hydrocarbons (PAHs), heavy metal accumulation, the emission of persistent free radicals, as well as possible soil microbiota disruption [7]. According to recent investigations, PAHs are formed primarily through gas-phase reactions and evaporation during the pyrolysis process, rather than through the actual carbonization reaction itself [8,9]. It implies that apart from feedstock composition and temperature of pyrolysis, factors such as reactor design, vapor residence time, as well as storage and post-pyrolysis treatment, can significantly affect contaminants' formation [10,11]. Even though much has been discovered within the field of biochar research, existing scientific sources remain scattered among numerous academic fields. Investigations devoted to the biochar production processes and contaminant formation usually differ from those studying soil health and agricultural productivity in terms of biochar application [12]. Such issues are especially critical when considering sustainable soil management using biochar, which not only provides soil structure improvement, nutrient storage, and promotion of microorganism activity, but also helps in overcoming negative effects like salinization of soil [3,13]. It means that there is a high need for careful consideration of biochar production conditions, physicochemical properties, contaminant formation, and their impacts on soils. This review provides a necessary overview of existing information regarding these aspects, addressing the following key points: (i) the role of production conditions for biochar physicochemical properties and contaminant formation, (ii) the impact of biochar on the physical, chemical, and biological soil properties, paying special attention to the salt-affected soils, and (iii) knowledge gaps in this area preventing biochar utilization standardization.

Overall, this paper proposes a systems-based perspective in which biochar should not be viewed as universally beneficial, but rather as a material whose effectiveness depends on both its production method and the conditions under which it is applied. Such an integrated understanding is essential for the safe and effective use of biochar in soil improvement and environmental remediation, while minimizing unintended ecological risks and soil chemical imbalances under specific environmental conditions.

2. Literature Review

2.1. Biochar Manufacturing and Physicochemical Characteristics

Biochar is obtained from the thermochemical conversion process of biomass material under oxygen-free environments, and the biogas and bio-oil are created as products, as illustrated in Figure 1 below [6,14,15]. It is important to note that the characteristics of biochar depend on various factors such as the temperature applied during pyrolysis, heating rate, residence time, and the types of biomass feedstocks used [16]. Research conducted before reveals that high temperatures during pyrolysis lead to increased levels of aromatics, porosity, and stabilization, coupled with reduced amounts of volatile substances within the biochar[17]. Conversely, biochar prepared under low temperatures possesses many surface functional groups and hence high CEC.[16,18].

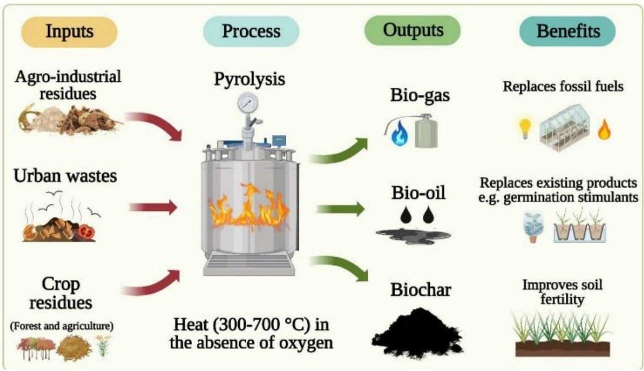

Figure 1. Biochar production processes (Wikipedia).

The type of biomass used is one of the critical aspects impacting the properties of biochar [19,20]. For example, lignocellulose-based materials give more stable and porous biochar [21,22], while manure-based feedstocks produce rich biochar characterized by high ash content [23]. However, while those variables are well-known, recent research findings suggest that the importance of reactor design and vapor phase dynamics is on par with each other when considering biochar quality

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outcomes [24,25]. Specifically, the synergies between the solid phase carbonization reaction and gas phase reactions during pyrolysis may have considerable impacts on the development of structure and secondary compound generation [26–28]. Nevertheless, reactor design and process engineering considerations appear to have been neglected in most previous studies on biochar production; it is becoming evident that reactor design also plays a major role in biochar properties and characterization.

Table 1. Comparison of Biochar Production Technologies.

Technology	Temperature (°C)	Biochar Yield	Energy Output	Maturity Level	Key Limitations
Pyrolysis	300-700	High	Moderate	High	Product variability
Gasification	>700	Low	High	Medium	Low biochar yield
HTC	180-250	Moderate	Low	Low	Limited data
Flash Carbonization	300-600	Moderate	Moderate	Low	Scale-up challenges

2.2. Formation and Composition of PAHs in Biochar

The presence of contaminants, especially polycyclic aromatic hydrocarbons (PAHs), in biochar is now a well-known environmental problem since these pollutants tend to be very persistent, toxic, and potentially carcinogenic [29,30]. According [16] A recently published study in ACS Sustainable Chemistry & Engineering (2022) reveals novel insights into the formation of PAHs during pyrolysis. Prior research indicated that PAH formation occurs predominantly in the solid char phase. Nevertheless, it has been established that PAH formation occurs primarily due to the recombination and condensation of gases in the process of pyrolysis[9,31]. Upon cooling of the pyrolysis system, gas-phase PAHs can deposit onto the surfaces of the biochar particles or accumulate in the pores of the biochar material [32,33] Thus, the vapor residence time and the rate of gas flow are two significant factors that affect PAH formation in this case[34]. In general, the high molecular weight (HMW) PAHs tend to form at higher pyrolysis temperatures, while LMW PAHs occur at lower temperatures.[35,36].

Notably, the study revealed that an efficient reactor design plays a crucial role in reducing PAH content. The systems that effectively get rid of volatile organic compounds and do not allow the formation of vapors can substantially reduce PAH formation [37]. At the same time, if the volatiles stay in contact with biochar for a long time, secondary reactions occur, which increase PAH formation [38]. This conclusion dispels a widely held belief about the key role of temperature in PAH production. Though considerable progress has been made regarding PAH contamination of biochar, many challenges remain. Among these challenges, regulatory issues concerning the product's safety should be singled out. Specifically, current regulations do not account for the heterogeneity of PAH composition.

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2.3. Biochar Application in Salt-Affected Soils

The positive effect of biochar application in salt-affected soils has been extensively researched in recent years, according to studies by[39]. The use of biochar leads to improvements in the physical, chemical, and biological qualities of salt- and sodic-affected soils [40,41]. In terms of chemical reactions, the use of biochar can affect ion dynamics through the absorption of soluble salts and the leaching of excess sodium ions [42,43]. Moreover, biochar can also play a vital role in providing essential cations, such as calcium and magnesium, that will replace sodium ions from exchange sites and balance soil cations [44,45]. These reactions result in decreased electrical conductivity (EC) and Sodium Adsorption Ratio (SAR), which are used as indicators of salt stress. [46,47].

From a biological perspective, biochar is known to provide a favorable habitat for soil microorganisms, enhancing microbial activity and enzyme synthesis [48,49]. As a result of increased biological activities, nutrient recycling and soil fertility are positively influenced [50]. Nonetheless, the impact of biochar on soils and its ability to promote microbial activities largely depend on its physicochemical properties, which are determined by production conditions [3]. For example, high-temperature biochar can be more stable than low-temperature biochar [51]. Although extensive literature exists on the agronomic benefits of biochar, very few studies have examined the potential effects of toxic substances, such as PAHs, on soil ecosystems. It is imperative to fill this knowledge gap, especially since biochar can be applied to soil over the long term.

Table 2. Positive and Negative Impacts on Soil.

Category	Benefits	Detrimental effects
Physical	Increased water holding capacity and porosity	Limited water availability (clay soils)
Chemical	Enhanced cation exchange capacity and nutrient retention	PH unbalance and salinity
Biological	Increased microbial activity	Microbe disruption
Environmental	Carbon storage	Heavy metals, PAHs

However, these advantages come with certain conditions that depend heavily on how biochar is produced.

2.4. Biochar Performance vs. Environmental Safety

Among the challenges faced in biochar research is ensuring a balance between the positive impact that biochar can have on agriculture and its negative impacts on the environment [52]. The scientific literature review reveals that agronomic studies tend to focus on the positive effects of biochar use, while environmental studies focus on contamination associated with biochar production. [3] These divergent research interests created a gap in understanding biochar. While biochar is considered a sustainable soil enhancer that promotes a climate-smart approach to agriculture, some doubt remains about its environmental safety. Only a few studies have addressed both problems by considering the impact of biochar production process parameters on its safety and functionality.

Another challenge in evaluating biochar performance is the lack of appropriate quality assessment measures. Most biochar testing standards cannot be applied because of the diversity of feedstocks, production conditions, and application procedures that characterize biochar systems. This necessitates the development of more advanced biochar assessment approaches that link biochar production processes to its safety and functions. Thus, from these findings, it follows that biochar should be used in accordance with local environmental conditions.

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2.4.1. Effect of Feedstock on Biochar

Biomass is mainly complex biological, non-organic, or renewable organic solid material derived from recently living organisms or microorganisms [53]. Biochar can be produced from various feedstocks, such as sawdust, agricultural materials, and food waste [54]. Adsorption of heavy metals can be affected by the type of feedstock [55]. The type of feedstock also plays a key role in biochar's pH [55]. Biomass also determines ash level and metal levels [16].

2.4.2. Effect of Temperature on Biochar

Biochar is usually produced between the temperatures of 200-1000 °C. under a limited or no Oxygen which is usually accomplished by passing Nitrogen gas through the tube[56]. Biochar properties differ at different temperatures [57]. Biochar determines the surface area and stability[58]. The yield of biochar reduces with an increase in temperature [59] higher temperature also favors the breakdown of calcium carbonate to calcium oxide and carbon dioxide, leading to an increase in the surface area of biochar [59] Biochar produced at high temperatures is more alkaline in nature [59]Temperature is an important environmental factor that imparts the stability of biochar-C in the soil [60], inorganic value of biomass reduced significantly near zero with an increase in temperature [61,62]

2.4.2. Soil Type

Soil differs in composition and particle size, which range from very fine to very coarse. There are other physicochemical properties like pH, moisture content, and every other property that enhance plant growth [63,64]. Soil structure determines how soil holds water and nutrients; this varies from one type of soil to another [65]. Previous findings show that biochar affects soil pH levels and dynamics [66]. Biochar application rate can affect toxicity or efficiency [67], aging/weathering of biochar also has long-term effects [68].

2.5. Research Gaps and Needs

While considerable advancements have been made in biochar studies, as shown in Table 3, some important areas still require attention (Table 4). First, studies on pyrolysis conditions, biochar characteristics, contamination, and soil function have not been integrated into a single study. Second, few agricultural investigations have focused on the importance of reactor design and the impact of vapor-phase dynamics on the production of high-quality biochar. Finally, the behavior of biochar and its contamination in soil systems over extended periods needs to be determined, especially in field conditions.

Table 3. Previous publications on Biochar production.

Authors	Year	Publication Tittle	Work conducted
Sebastian Meyer, Bruno Glaser & Peter Quicker	2011	Technical, Economic, and Climate-Related Aspects of Biochar Production Technologies: A Literature Review	Conducted an evaluation of different biochar production technologies, such as pyrolysis, gasification, hydrothermal carbonization, and flash carbonization, in addition to their economic and climate impact
P. R. Yaashikaa, P. Senthil Kumar, Sunita Varjani & A. Saravanan.	2020	A critical review of the biochar production techniques, characterization, stability, and applications for the circular bioeconomy	Assessed biochar production process and its application, as well as other attributes like physicochemical properties, stability, and environmental management.
Duo Wang, Peikun Jiang, Haibo Zhang & Wenqiao Yuan.	2020	Biochar production and applications in agro and forestry systems: A review	Conducted an evaluation of the biochar production process and its applications in agro and forestry systems.
James A. Ippolito et al.	2020	Feedstock choice, pyrolysis temperature, and type influence biochar characteristics: a comprehensive meta-data analysis review	Performed a meta-review on the effects of feedstock, pyrolysis temperature, and biochar production methods on the properties and behavior of biochar.
Xiaojiao Zhang et al.	2022	A critical review of the production, modification, and utilization of biochar	Explored the correlations between feedstock, biochar production parameters, biochar modification, and application in

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			environmental remediation and agriculture.
Yize Li, Rohit Gupta, Qiaozhi Zhang & Siming You	2022	Review of Biochar Production via Crop Residue Pyrolysis: Development and Perspectives	Provided a review on biochar production using crop residues pyrolysis, factors affecting biochar yield and quality, and future trends.
Mahesh Ganesapillai et al.	2023	Waste to energy: A review of biochar production with emphasis on mathematical modeling and its applications	Reviewed the biochar production technologies, including mathematical modeling and optimization for waste-to-energy applications.
Sahan Safarian	2023	Performance analysis of sustainable technologies for biochar production: A comprehensive review	Conducted a review of sustainable biochar production technologies, reactors, operational conditions, and effects on biochar properties and uses
Vishal Rajput et al.	2024	Biochar production methods and their transformative potential for environmental remediation	Discussed the current biochar production process and its effectiveness in pollution prevention, sewage treatment, and environmental remediation.
EB Agyekun, C Nutakor	2024	Recent advancement in biochar production and utilization – A combination of traditional and bibliometric review	Performed a review by combining both bibliometric and traditional approaches to examine the latest developments, trends, and diverse

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			applications of biochar technologies.
F Amalina et. al.	2022	Biochar production techniques utilizing biomass waste-derived materials and environmental applications – A review	Conducted a review of the biochar production process using biomass waste-derived feedstock and its environmental applications, including sewage treatment.

Table 4. Important Research Gaps.

Topic	Gap	Needed
Field studies	Insufficient long-term data	Multi-year experiments
Standardization	Lack of standardized procedures	International standards
Toxicity	Thresholds for toxicants	Negative health effects
Scale-up	Small-scale lab studies	Industry-level verification

Such issues require an approach grounded in contributions from process engineering, environmental chemistry, and soil science. Future research could focus on developing standardized methods for analyzing biochar, including its positive features and potential contaminants. Moreover, there is a need for long-term field experiments to assess the safety of biochar use under various soil conditions.

3. Conceptual Framework: Connecting Biochar Production, Contaminant Formation, and Soil Functionality

With a rapidly expanding body of studies on biochar, it is increasingly clear that the efficiency of biochar application to soils must be considered alongside biochar production. However, current studies tend to treat the different stages of this process as isolated entities, hindering a comprehensive understanding of the problem. To improve understanding, the present conceptual framework connects the conditions of biochar production, the physical and chemical properties of biochar, the behavior of contaminants, and soil function. The developed framework includes four interrelated parts: Pyrolysis Conditions, Physicochemical Characteristics of Biochar, Contaminant Dynamics and Distribution, and Functions of Soil and Its Environmental Performance. These parts are dynamically related to the main driver being pyrolysis conditions.

3.1. Production Conditions as the Primary Control

The parameters associated with biochar production, including pyrolysis temperature, heating rate, residence time, feedstock, and reactor type, are the primary factors that determine biochar quality. While the traditional focus was on temperature and feedstock, new research evidence presented [69] has emphasized the importance of reactions in the vapor phase, gas flow dynamics, and reactor design in affecting both biochar properties and contamination[16]. In this approach,

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production conditions are understood to impact two concurrent processes: Solid-phase reactions that result in the formation of carbon structure, porosity, and surface chemistry, and Gas-phase reactions that result in the formation of volatile substances and by-products such as PAHs. The interplay of these two processes determines the biochar produced.

3.2. Physicochemical Properties Development of Biochar

The physicochemical properties of biochar, including its surface area, porosity, aromacity, functional group composition, and mineral content, determine how the substance interacts with soils[16]. It has been reported that high-temperature pyrolysis creates biochar with higher structural stability and surface area, while low-temperature biochar holds more functional groups, promoting nutrient exchange and microbial growth[16].

In the same manner, physicochemical properties are considered functional components that influence soil improvement through various mechanisms, including water retention and infiltration, nutrient uptake and release, cation exchange capacity (CEC), and the formation of microbial habitats; however, these positive characteristics should be weighed against any contaminants generated during production.

3.3. Contaminant Formation and Deposition Mechanisms

One key element of this approach is considering the role of contaminants, specifically the formation and deposition of PAHs. In accordance with the study, PAHs are mainly formed in the gaseous state and deposited on biochar particles upon cooling[25].

The mechanism is influenced by: The duration of vapor presence in the air, temperature differences, the efficiency of volatile elimination, and the cooling process post-pyrolysis[70,71].

Moreover, the model highlights the difference between Conventional formation mechanisms (gas-phase production of PAHs) and conventional deposition mechanisms (adsorption and condensation on biochar particles). This differentiation plays an essential role, as it indicates the possibility of minimizing contamination not only through temperature regulation but also through reactor optimization.

3.4. Soils' Functionality and Agronomic Performance

The goal of biochar application is to enhance overall soil quality and fertility. According to research, in saline-affected soils, biochar increases soil structural stability, reduces the impact of salts, and improves the biological activity of soils [13,72,73]. Such outcomes can be achieved due to the interaction of soil and biochar characteristics in terms of ion exchange, agglomeration, and biological properties [74]. Following the framework, biochar functionality is understood as the result of two concurrent influences on soil: its beneficial effects, related to biochar's physicochemical features, and its disadvantages, arising from the presence of various pollutants, for instance, PAHs.

3.5. Trade-Offs and Optimization Strategies

An important aspect of this framework is its recognition of trade-offs between maximizing agronomic advantages and minimizing environmental disadvantages. For instance, Temperature increases can enhance stability [61] but lead to the generation of high molecular weight PAHs [60], gas stripping rates can optimize carbon content, but increase contamination deposition [75], high nutrient levels in feedstock can enhance soil enrichment but cause salinity and trace contamination [76]. The trade-offs highlight the importance of adopting a multi-objective optimization approach to biochar production. Instead of focusing on a single variable, the framework underscores the importance of incorporating multiple process factors to achieve a balance among soil fertilization, environmental safety, and long-term sustainability.

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Table 5. Evolution of Biochar Research (2011–2025).

Aspect	Early Research (≤2011)	Recent Research (2015–2025)
Focus	Production & climate	Soil health & risks
Technology	Pyrolysis dominant	Engineered biochar
Benefits	Carbon sequestration	Multi-functional (remediation, soil)
Risks	Minimally discussed	Strongly emphasized
Data scale	Lab-based	Field + meta-analysis
Conclusion	Promising solution	Context-dependent tool

Biochar research conducted over the last few years has made a considerable contribution to understanding how biochar interacts with the soil system. At first, studies focused on its ability to store carbon dioxide and improve soil properties; later research revealed the multifaceted nature of biochar's behavior in soil. Variations in biochar structure due to differences in initial material, processing technology, and environmental factors affect not only positive but also negative consequences. Furthermore, recent issues regarding pollutant accumulation, altered soil fauna, and biochar stability are raising questions about its sustainability. Developing biochar from a promising but still speculative technology into a solid one requires a paradigm shift from individual approaches towards system-level approaches. By aligning production science with environmental safety and soil functions, future work can pave the way for the design of biochar systems.

3.7. Importance of Reactor Design and Process Engineering

Despite extensive research on the influence of temperature and feedstock properties, less attention has been paid to reactor design and gas-phase reactions[77]. It is important to investigate further how to regulate vapor retention time, improve the effectiveness of volatile compound elimination, understand the influence of scaling and reactor design, and analyze cooling system efficiency.

Today, biochar analysis is primarily conducted by measuring total carbon content and total PAH concentration[25]. It is necessary to improve current approaches by introducing a complex system for assessing biochar quality using multiple criteria, including classification of PAHs into high- and low-molecular-weight groups, development of bioavailability risk assessment, and adherence to international safety standards[78,79].

Many of the studies were conducted in laboratory conditions over short periods. Therefore, future studies should focus on long-term field testing to clarify aspects such as biochar's long-term effects on soil enhancement[80], the long-term mobility and persistence of PAHs in soils, interactions between soil microbes and biochar, and interactions between organic matter and biochar under various climatic conditions.[81,82]

Additional studies should also be conducted on biochar performance under multiple-stress conditions, including salinity and sodicity, poor and acidic soils, and industrially contaminated soils[83,84]. The exploration of these complex factors will enable scientists to better understand biochar's performance under different environmental conditions[84].

The other innovative trend is the implementation of safe-by-design biochar technology that will enhance soil performance, prevent contaminant formation, and ensure biochar characteristics that match those of stressed soils.[85,86]

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Finally, It is critical to determine whether PAHs remain adsorbed to biochar particles or whether their biological activity emerges[87], whether PAH degradation occurs due to microbiological activity in the soil environment, and what ecological risks are associated with this process.[88]

3.8. Conclusion

Biochar is a versatile form of carbon-based material with tremendous promise in the areas of carbon sequestration, soil amendment, and the sustainable remediation of saline soils. The effectiveness of biochar largely depends upon its composition and characteristics, which are affected by the type of feedstock, the method of production, and the chemical transformation process. Research conducted thus far has found that biochar increases soil structure and nutrient content, alleviates the effects of salinity, and promotes microbial life within the soil.

Another aspect covered in this review article includes the impact of organic contaminants, specifically polycyclic aromatic hydrocarbons (PAHs), during biochar preparation. Based on recent research results, it is evident that PAH formation during the production of biochar is not affected by changes in pyrolysis temperatures alone but is dependent upon other factors including gas phase reactions, vapor residence time, reactor configuration, and post-production treatments.

This review has provided a comprehensive platform that connects the production procedures, properties of biochar, formation of contaminants, and soil reactions to each other. In addition, it has made it clear that biochar cannot be regarded as one single substance, since its properties are quite heterogeneous depending on the procedure that is applied in its production.

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