

Review

Biochar Production: Toward Safe, Effective, and Sustainable Agriculture

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Abstract

Biochar, a carbon-rich product resulting from the thermochemical transformation of organic biomass under limited oxygen condition, 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 factors like feedstock type, process conditions, biochar properties, and other factors. While biochar exhibits multiple beneficial 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



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1. Introduction

Biomass is a complex biological material composed of renewable organic matter derived from recently living plants, animals, or microorganisms [1]. Biochar is a carbonaceous material produced through the pyrolysis of biomass and can be manufactured from a wide range of feedstocks, including sawdust, agricultural residues, and food waste [2]. Biochar is typically produced at temperatures ranging from 200 to 1000 °C under limited oxygen conditions, which is usually accomplished by purging the reactor with Nitrogen gas [3,4]. The physicochemical properties of biochar vary considerably with pyrolysis temperatures [5]. Temperature strongly influences properties such as surface area, porosity, chemical composition, and stability [5]. Generally, biochar yield reduces as pyrolysis temperature increases because of thermal decomposition of the biomass [6]. Higher temperature also promotes the breakdown of calcium carbonate to calcium oxide and carbon dioxide, which can

contribute to an increase in the surface area of biochar [7]. In addition, biochar produced at high temperatures is more alkaline in nature due to the concentration of mineral ash and loss of acidic surface functional groups [7]. Conversely, the volatile organic fraction of biomass decreases substantially with an increase in pyrolysis temperature, resulting in more carbonized and stable biochar [8].

Early studies demonstrated that biochar is technically and economically viable and can contribute to greenhouse gas mitigation, encouraging the application of biochar in sustainable agriculture and environmental management [9]. Initially, the primary benefits of biochar were attributed to its high carbon stability and its potential to improve degraded soil, thereby enhancing agricultural productivity. Subsequent research, however, revealed that biochar behavior in soil is more complex and that its effectiveness depends on several factors, including pyrolysis temperatures, feedstock type, and the reactor design [9]. Moreover, the performance of biochar is strongly influenced by environmental conditions, which govern its interaction with soil minerals, microorganisms, nutrients, and contaminants [4,10,11].

On the other hand, concerns have been raised about the safety of using biochar in agriculture 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 [9]. 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 [12,13]. It implies that apart from feedstock composition and the temperature of pyrolysis, factors such as reactor design, vapor residence time, as well as storage and post-pyrolysis treatment can significantly affect contaminant formation [14]. 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 [15]. 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 soil salinization. This 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: (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 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. Methodology and Scope of the Review

The review was performed through a logically arranged discussion of the current and relevant literature on biochar production, its physical and chemical characteristics, contaminant formation (especially polycyclic aromatic hydrocarbons, PAHs), and appli-

cation in salt-affected soils. Peer-reviewed articles were obtained mainly through Web of Science, Scopus, and Google Scholar searches using keywords such as “biochar production,” “pyrolysis conditions,” “reactor design,” “PAHs in biochar,” “biochar safety,” and “saline soil remediation. Publication years from 2010 to 2025 were preferred to ensure that both the foundational and most recent advances in the subject were collected. Research papers were selected based on whether they considered the following points: (i) production conditions and biochar physicochemical properties and contaminant formation, especially PAHs, (ii) the impact of biochar on the physical, chemical, and biological soil properties, paying special attention to salt-affected soils, and (iii) knowledge gaps in this area preventing biochar utilization standardization. All other studies focused mainly on the use of biochar for energy purposes and were excluded from this study.

2.2. Novelty and Contribution of This Review

By merging three different fields—biochar production, contamination, and application in soils—this paper provides an integrated approach towards these aspects. The novelty of this work is seen through the integration of the following three factors:

1. Pyrolysis conditions and reactor design;
2. Forming and depositing mechanisms of PAHs;
3. Physical and chemical properties.

2.3. Biochar Manufacturing and Physicochemical Characteristics

Biochar is obtained from the thermochemical conversion process of biomass material under oxygen-free environments, yielding solid biochar along with gaseous syngas and liquid bio-oil [16], as illustrated in Figure 1 below. The overall process is strongly influenced by pyrolysis parameters, including temperature, heating rate, residence time, feedstock composition, and reactor configuration [3]. Temperature has been known to be an important variable that determines the characteristics of biochar [5]. Generally, high pyrolysis temperatures (500–800 °C) (Table 1) result in biochar with high aromaticity, surface area, structural stability, and low volatile contents, while low temperatures lead to the presence of more oxygen functional groups that improve CEC and nutrient interactions [17].

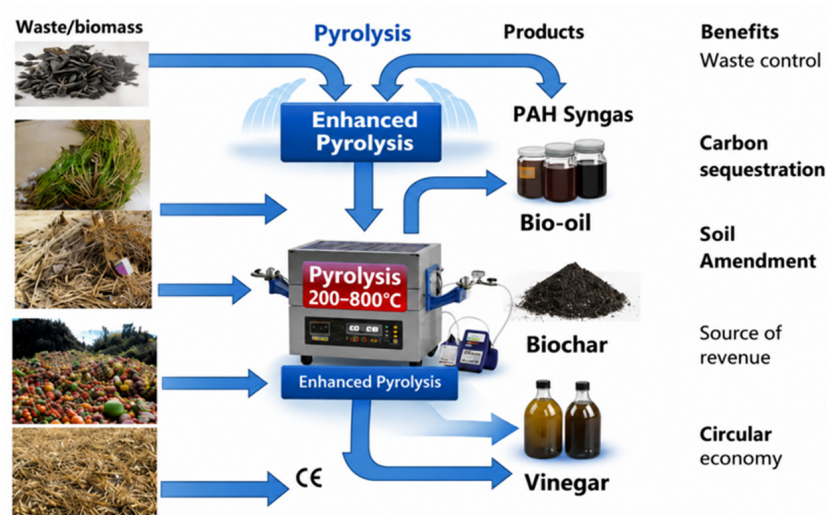


Figure 1. Biochar production processes.

In addition, the source material has a great impact on the process as well. Biomass with lignocellulosic origin yields biochar with higher porosity and structural stability, while materials of animal origin yield biochar with high ash content and nutrients. The type

of biomass used is one of the critical aspects impacting the properties of biochar [18–20]. However, recent research findings point out that focusing on temperature and materials as the only variables makes the explanation of biochar formation too simplistic. The design of the reactor and the vapor phase play an important role in secondary reactions, pore formation, and the chemistry of the surfaces; e.g., incomplete removal of volatiles leads to the formation of intermediate products due to condensation reactions [13]. 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 compounds [13]. Nevertheless, 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. Biochar production technologies: a comparative analysis.

Technology	Operating Conditions	Biochar Yield	Product Quality	Energy Recovery	PAHs Emission	Sustainability for Soil Application	Key Limitation
Pyrolysis	200–700 °C limited O ₂	High	Medium to high (Depending on temperature)	Moderate	Medium PAHs increase at high T and poor reactor control	High (Most widely used)	Sensitive to reactor design and feedstock variability
Gasification	>700 °C	Low	High aromaticity but low yield	High	Low to medium (Lower PAHs but more syngas emission)	Low	Poor biochar yield limits soil use
Hydrothermal Carbonization (HTC)	180–250 °C, Wet biomass	Moderate	Low to medium stability	Low	Low to medium (Oxygenated organics present)	Medium (Better for wet waste)	Limited field validation and low carbon stability
Flash carbonization	300–600 °C, rapid heating	Moderate	Variable (Heterogeneous structure)	Moderate	Medium (depends on vapor control efficiency)	Medium	Scale-up and process control challenges

Polycyclic aromatic hydrocarbons (PAHs) are some of the most important contaminants in relation to biochar production due to their persistent character, toxicity, and carcinogenic properties [21]. A recently published study in *ACS Sustainable Chemistry & Engineering* (2022), reveals novel insights into the formation of PAHs during pyrolysis. The reported levels of $\Sigma 16$ PAHs in biochar are usually between 1 and 100 mg kg^{−1} for most production methods. In the case of unfavorable production conditions, however, levels of 355 mg kg^{−1} can be found. On a per-production-unit basis, this is equivalent to between 1 and 100 g of PAHs per ton of biochar, with exceptional levels at 355 g ton^{−1}. In the case of low-PAH biochar, however, its production level should be around 4 to 12 g ton^{−1} [22,23]. Prior research indicated that PAH formation occurs predominantly in the solid char phase. However, it has since been established that PAH formation occurs primarily due to the recombination and condensation of gases in the process of pyrolysis [13]. 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. Thus, the vapor residence time and the rate of gas flow are two significant factors that affect PAH formation in this case [24]. In general, high molecular weight (HMW) PAHs with 4–6 rings tend to form at higher pyrolysis temperatures, while LMW PAHs with 2–3 rings occur at lower temperatures [25–27]. An important controlling factor here is vapor residence time. High residence time and poor gas removal are also influential factors.

This study notably revealed that efficient reactor design is crucial to reducing PAH content. Systems that effectively get rid of volatile organic compounds and do not allow the formation of vapors can substantially reduce PAH formation [28]. At the same time,

if volatiles stay in contact with biochar for a long time, secondary reactions occur, which increase PAH formation [13]. This conclusion dispels a widely held belief about the key role of temperature in PAH production. Although considerable progress has been made in addressing PAH contamination in biochar, many challenges remain. Among these challenges, regulatory issues concerning the product's safety should be singled out.

2.4. 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. The potential of biochar as a soil amendment material for improving soils affected by salt and sodicity has been extensively researched. It works through physical and chemical properties [29]. The use of biochar leads to improvements in the physical, chemical, and biological qualities of salt- and sodic-affected soils [30]. 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 [31,32]. 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 [33,34]. These reactions result in decreased electrical conductivity (EC) and Sodium Adsorption Ratio (SAR), which are used as indicators of salt stress [9].

From a biological perspective, biochar provides a favorable habitat for soil microorganisms, thereby enhancing microbial activity and enzyme synthesis [11,35,36]. As a result of increased biological activities, nutrient recycling and soil fertility are positively influenced [37]. 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 [11]. For example, high-temperature biochar can be more stable than biochar produced at lower temperatures [38]. Although extensive literature exists on the agronomic benefits of biochar, relatively few studies have examined the potential effects of toxic substances, such as PAHs, on soil ecosystems (Table 2). Addressing this knowledge gap is imperative, particularly because biochar is often applied to soil and may persist for extended periods.

Table 2. Impacts of biochar on soil.

Soil Function	Beneficial Effect of Biochar	Negative Effect of Biochar	Production Condition
Physical properties	Improve porosity and water retention	May retain water in clay-rich soil if applied in large quantities	Largely influenced by pyrolysis temperature and feedstock
Chemical Properties	Increase in pH buffering, CEC, and nutrient retention	Might lead to an imbalance in salinity or nutrient localization	High temperature increases biochar alkalinity
Biological activity	Soil sequestration	Likelihood of microbial imbalance if contaminated with PAHs or heavy metals	Highly connected to PAN content and Ash composition
Environmental Function	Carbon sequestration and soil movement	Risk of contamination due to accumulation of PAHs and heavy metals	Influenced by reactor design and feedstock purity

These advantages come with certain conditions that depend heavily on how biochar is produced.

2.5. Biochar Performance vs. Environmental Safety

Biochar shows promising results for soil fertilization and carbon accumulation; however, concerns remain about contaminants, such as PAHs, heavy metals, and other organic compounds left after pyrolysis. Among the concerns is ensuring a balance between the

positive impact that biochar can have on agriculture and its negative impact on the environment [21]. The existing literature either addresses soil improvement effects or describes contaminant characteristics but does not consider both aspects. 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, these findings indicate that biochar should be used in accordance with local environmental conditions. There is a need for an improved methodological approach addressing the following issues:

- HMW and LMW PAH distribution;
- PAHs' bioavailability and leaching capacity;
- Aging processes in soil-biochar system;
- Long-term ecological effects in field conditions.

These 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.

2.6. 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.

Study	Focus Area	Key Contributions	Strength	Limitation/Gap
Meyer et al. (2011) [39]	Production technology and climate impact	Compared to pyrolysis, gasification, HTC	Foundational framework	Limited environmental contamination analysis
Yaashika et al. (2020) [40]	Characterization and application	Linked properties to the application	Broad overview	Lack of mechanistic PAH discussion
Joseph et al. (2021) [41]	Agroforestry application	Soil application benefits	Strong applied forces	Weak process engineering insight
Ippolito et al. (2022) [42]	Meta-analysis of feedstock & temperature	Identify key property drivers	Strong statistical synthesis	Limited reactor design consideration
Zhang et al. (2022) [43]	Modification and remediation	Biochar functionalization strategies	Application oriented	Limited long-term soil risk analysis
Li et al. (2023) [44]	Crop residue pyrolysis	Yield and production optimization	Process-focused	Weak environmental safety coverage

Table 3. Cont.

Study	Focus Area	Key Contributions	Strength	Limitation/Gap
Ganesapillai et al. (2023) [45]	Modeling & optimization	Mathematical process modeling	Strong engineering	Limited soil interaction focus
Safarin (2023) [46]	Sustainable technologies	Process sustainability evaluation	Good technology economic analysis	Limited contaminant discussion
Rajput et al. (2024) [47]	Environmental remediation	Pollution mitigation application	Applied environmental focus	Limited threshold discussion
Wu et al. (2024) [48]	Bibliometric + review	Trend mapping of biochar research	Broad perspective	Lacks mechanistic depth
Amalina et al. (2022) [49]	Waste biomass conversion	Waste-to-biochar pathway	Circular economy focus	Limited PAH and toxicity assessment

Table 4. Important research gaps.

Research Domain	Current Limitation	Why it Matters	Required Advancement
Field Validation	Mostly short-term lab studies	Limited real-world applicability	Long-term multi-site field trials
Standardization	No unified testing protocols	Results are not comparable across studies	International biochar safety standards [50]
Toxicity Assessment	Focus on total PAHs only	Underestimates environmental risks	PAH speciation + bioavailability analysis
Reactor design	Often ignored in the literature	Control PAH formation and biochar quality	Integrated reactor chemistry models
Scale-up studies	Laboratory-scale-up dominance	Weak industrial translation	Pilot and industrial validation
Soil Interaction	Limited long-term monitoring	Unknown persistence and aging effects	Multi-year soil–biochar interaction studies

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, which is pyrolysis conditions.

3.1. Production Conditions as 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 [51] has emphasized the importance of reactions in the vapor phase, gas flow dynamics, and reactor design in affecting both biochar properties and contamination [5]. In this approach, 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.

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 [23]. Low-temperature biochar (300–400 °C) typically yields 0.1–5 mg/kg total PAHs. Moderate conditions (400–600 °C) produce approximately 1–50 mg/kg. High-temperature or poorly controlled systems can exceed 50–300 mg/kg, especially high molecular weight PAHs [7]. 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 [52,53].

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.

3.2. Soil's Functionality and Agronomic Performance

The primary goal of biochar application is to improve overall soil quality and fertility. Soil varies in composition and particle size, which ranges from very fine to very coarse. There are other physicochemical properties, like pH, moisture content, cation exchange capacity, organic matter content, and porosity, that play an essential role in plant growth [54]. Soil structure determines its capacity to retain water and nutrients; these characteristics vary among different types of soil [9]. Previous findings show that biochar can significantly influence soil pH and its associated chemical and biological processes [11]. Furthermore, the application rate of biochar is a critical factor, as excessive or insufficient amounts may reduce its effectiveness [55]. The aging or weathering of biochar also influences its long-term performance by altering its physicochemical properties and interaction with soil over time [56].

According to research, in saline-affected soils, biochar increases soil structural stability, reduces the impact of salts, and improves the biological activity of soils [57,58]. Such outcomes can be achieved due to the interaction of soil and biochar characteristics in terms of ion exchange, agglomeration, and biological properties [59]. 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.

3.3. 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 but lead to the generation of high molecular weight PAHs [60]. Gas stripping rates can optimize carbon content but increase contamination deposition [61]. High nutrient levels in feedstock can enhance soil enrichment but cause salinity and trace contamination [62]. The trade-offs highlight the importance of adopting a multi-objective optimization approach to biochar production. Rather than 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.

Research conducted over the last few years has made a considerable contribution to understanding how biochar interacts with the soil system (Table 5). 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 feedstock, 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.

Table 5. Evolution of biochar research (2011–2025).

Aspect	Early Research (≤ 2011)	Recent Research (2015–2025)
Focus	Production and climate	Soil health and 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

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.

3.4. 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. It is important to investigate how to regulate vapor retention time, improve the effectiveness of volatile compound elimination, understand the influence of scaling and reactor design, and analyze the efficiency of the cooling system. Previous research shows that reactor design significantly affects PAH contamination by controlling vapor residence time and volatile removal. Buss et al. reported that increasing carrier gas flow in a batch fixed-bed reactor reduced total EPA-16 PAHs from 43.1 to 3.5 mg kg^{−1} for straw biochar and from 7.4 to 1.5 mg kg^{−1} for woody biochar, corresponding to approximately 92% and 80% reductions, respectively. These findings demonstrate that efficient vapor evacuation and reduced condensation can substantially decrease PAH deposition [22]. Continuous reactors vs. batch systems typically generate 30–70% lower PAH accumulation. Vacuum or reduced-pressure pyrolysis can reduce PAHs by ~50–90%, particularly the high-molecular-weight fractions. Rapid quenching or improved cooling systems can reduce PAH re-condensation by ~25–60% [63]. Today, biochar analysis is primarily conducted by measuring total carbon content and total PAH concentration. It is necessary to improve current approaches by introducing a comprehensive system for assessing biochar quality using multiple criteria, including classifying PAHs into high- and low-molecular-weight groups, developing a bioavailability risk assessment, and adhering to international safety standards [64,65].

Many of the existing studies have been conducted under laboratory conditions over relatively short periods. Therefore, future studies should prioritize long-term field studies to better understand biochar's long-term effects on soil quality and fertility, the mobility and persistence of PAHs in soil, interaction between biochar and soil microbial communities, and the interactions between biochar and soil organic matter under diverse climatic conditions [66–68].

Further studies should also evaluate biochar performance under multiple-stress conditions, including saline–sodic soils, nutrient-poor and acidic soils, and industrially contami-

nated soils [69,70]. Investigating these complex factors will provide a more comprehensive understanding of biochar's performance across different environmental conditions [70].

Another innovative research direction is the development and implementation of safe-by-design biochar technologies that optimize soil improvement while minimizing contaminant formation and producing biochar with physicochemical properties tailored to the specific requirements of stressed soils [71,72].

Finally, it is essential to determine whether PAHs remain adsorbed to biochar particles or become bioavailable over time [73], to investigate the extent to which soil microbial activity contributes to PAH degradation, and to evaluate the ecological risks associated with the transport, transformation, and persistence of PAH in the soil environment [74].

4. Polycyclic Aromatic Hydrocarbons (PAHs) in Biochar Systems: Formation, Retention, and Environmental Fate

PAHs comprise a large group of chemicals with fused persistent aromatic rings formed through incomplete combustion of inorganic matter from natural (volcanic eruption and forest fires) and anthropogenic (industrial, as well as vehicular and residential) sources [13]. The appearance of PAHs in biochar does not stem from a unique mechanism but includes a series of mechanisms, including primary decomposition, secondary transformation in the gas phase, and final deposition after formation [75]. Cellulose and hemicellulose produce oxygenated volatiles, while lignin produces aromatic moieties, which serve as precursors of PAHs [76]. In turn, at high temperatures, these intermediates undergo processes of cracking, cyclization, dehydrogenation, and condensation, resulting in the creation of fused aromatic compounds [13]. Further, gas-phase chemistry transforms the molecular composition of PAHs, especially in cases when pyrolysis gases are retained in regions of high temperatures for a sufficient period to enable secondary aromatization and molecule growth [77].

Whether or not the above-mentioned processes will be able to result in PAH contamination largely depends on the reactor type, reaction severity, and properties of the feedstock [5]. The reactor design controls efficient heat transfer, vapor extraction, and the level of vapor–char contact, affecting thereby both the formation and deposition of PAHs [78]. Processes that favor extended retention of vapor and its contact with char will produce more favorable conditions for the secondary formation and deposition of PAHs, while fast vapor extraction and efficient quenching may help minimize their content in the resulting biochar [23]. Therefore, the rate of cooling becomes an important aspect that, besides being a process parameter, controls the kinetics of PAH deposition, because at low cooling rates there will be more chances for semi-volatile substances to deposit on the surface of the porous carbon material [79].

The impact of feedstock properties cannot be underestimated either [80]. The presence of lignin in feedstock will supply aromatic components for PAH formation, while the presence of extractives, lipids, ash components, and mineral catalysts in feedstock will modify devolatilization processes and secondary reactions in the vapor phase [5,81].

The environmental relevance of PAHs in biochar beyond their generation depends on the ways by which they are stabilized, sequestered, and possibly released after production [82]. Pore structure and biochar surface chemistry are key factors in this context [82]. While microporous sites can provide strong confinement for PAHs and reduce their extractability, mesopores allow for their diffusion and dynamic exchanges with the surrounding medium [83]. Sorption mechanisms can include the partitioning into hydrophobic sites and π - π interactions of PAHs with aromatic carbon domains, supplemented by the adsorption onto functional groups containing oxygen and mineral surfaces, which play a secondary role in this process [84]. Such mechanisms make the interpretation of detected levels of PAHs difficult, since the total amount of PAHs does not always coincide with the

environmentally available fraction of PAHs [85]. Despite the high content of PAHs in the given biochar, short-term release can be rather limited due to the sequestration of these compounds within the aromatic carbon matrix or porous system of the biochar.

The long-term fate of PAHs in biochar-enhanced soils will be further influenced by aging, colloidal transport, and the disconnect between lab and field data [86]. Upon addition to the soil, biochar surfaces will be oxidized, wet and dried, interact with minerals, and be colonized by microbes, which may influence the pore accessibility, surface polarity, and mobility of contaminants [15]. This may either increase sequestration through enhanced sorption and pore entrapment or decrease sequestration by altering the surface properties and creating new accessible routes for transport [87]. Biochar particles and colloids may also serve as carriers for sorbed PAHs, forming an additional means of transport that is seldom studied in batch experiments. Therefore, the total amount of PAHs will not provide a complete picture of the risks posed by biochar; the bioavailability, mobility, and persistence will depend on the dynamic interplay of biochar history, biochar properties, and post-treatment soil processes. To create a safe-by-design procedure of biochar preparation, one should not only reduce PAH formation via proper choice of feedstocks, reactor conditions, vapor control, and cooling procedures, but also study the dynamics of biochar behavior in the environment under the regulation of contaminant threshold levels within a certifying body.

5. Other Contaminants, Certification Standards, and Broader Risk Indicators in Biochar Systems

Besides PAHs, other factors that contribute to the overall safety assessment of biochar include inorganic impurities, reactive surface species, and various thermochemical by-products, the presence of which depends heavily on the feedstock used for production. Heavy metals and metalloids pose an additional risk because, unlike PAHs, they are not produced during pyrolysis but can accumulate in biochar due to mass loss and ash enrichment that occur during the process [9]. Consequently, the concentration of heavy metals and metalloids in biochar is primarily determined by the feedstock composition. Feedstocks such as sewage sludge, biosolids, manure, and some industrial or municipal waste generally contain higher concentrations of heavy contamination than pure lignocellulosic biomass. However, total metal concentration alone does not adequately reflect the potential danger posed by heavy metals and metalloids. Pyrolysis alters the chemical speciation, mineral associations, and solubility, thereby influencing their mobility and availability when applied to soil [88]. Consequently, pyrolysis temperature, ash composition, pH, and the redox reactivity of mineral phases determine whether Cd, Pb, Zn, Cu, Cr, and Ni will be immobilized within the biochar matrix or will be available to the surrounding environment [89].

Persistent free radicals (PFRs) form another unique yet important group of biochar-linked contaminants since they can be generated during the process of thermochemical transformation and possibly persist within the structure of carbon for long periods of time, even after the manufacturing process has been completed [90]. PFRs are generally stabilized via the formation of condensed aromatic clusters or redox-active centers associated with minerals and depend on such factors as the temperature of the pyrolysis process, presence of oxygen, degree of carbonization, and transition metal content, including such elements as Fe, Cu, and Mn [91]. The main impact of PFRs on the environment includes their ability to generate reactive oxygen species, interfere with microbial functioning, and induce oxidative stress in living organisms [92]. Consequently, the occurrence of PFRs depends on the same characteristics of the biochar structure that often improve its sorption properties and stability, thus creating additional risks that must be addressed by biochar users. Apart from

PFRs, fresh biochar may contain traces of such substances as volatile organic compounds and tar residues, which cause odors, phytotoxic effects, or biochar instability due to vapor removal failure and lack of post-process treatment [93].

Although there is no universally defined “zero-risk” threshold for PAH, the diversity of contaminant types in biochar raises issues associated with the need to establish certification standards and threshold-based quality control systems. In particular, current certification schemes such as those suggested by the International Biochar Initiative (IBI) and the European Biochar Certificate (EBC) have played a crucial part in the establishment of acceptable levels of contaminants, including PAHs and heavy metals, as well as the definition of traceability requirements, test protocols, and use categories for the products [94,95]. These certification systems have contributed significantly to improving the uniformity of commercial biochar assessment and have provided a reliable way to differentiate between biochars that can be used for agricultural purposes and those that must be used only under certain restrictions. For example, the Occupational Safety and Health Administration sets a legally enforceable exposure limit of 0.2 mg/m³ of air over an 8 h workday (OSHA), while the National Institute for Occupational Safety and Health recommends a stricter threshold of 0.1 mg/m³ for a 10 h workday (NIOSH) [96]. However, certification thresholds must not be considered as a complete replacement for environmental safety criteria. In most cases, standards are established mainly based on contaminant concentrations, whereas the speciation of contaminants, their bioavailability, effects of aging, and interactions among different contaminants, such as metals, PAHs, radicals, salinity, and volatiles, are not completely accounted for. Thus, meeting regulations is an essential step but not a full-scale explanation of the risks associated with biochar.

It is thus imperative to move towards a more comprehensive approach by shifting away from the practice of single-contaminant screening to evaluate the interactions between biochar, soil, plant life, and microbial community through time. Biological effects observed due to addition of biochar, such as increase in microbial activity, inhibition effects, oxidative stress, and nutrient cycling, cannot be associated with the presence of only one contaminant; rather, they result from the cumulative impact of several factors, including pH changes, salinity, nutrients release, presence of residual organics, metals bioavailability, PFR activities, and changes in surface chemistry. In this context, the discrepancy between results obtained in laboratory-scale tests and those found in the field can have different origins, including weathering effects, aggregation processes, dissolution of organics, and root-microorganism interactions. For this reason, the production of safe biochars should be considered from a holistic point of view in which contaminant reduction, certification, and environmental fate are considered together along with feedstock choice, pyrolysis process, post-processing steps, and application conditions.

6. Environmental Performance, Aging, Field Behavior, and Long-Term Safety of Biochar

In addition, the environmental performance of biochar cannot be judged based on its physicochemical characteristics alone, because its reactions and transformations occur while interacting with water, minerals, microorganisms, and plant roots in soil after soil application [87]. Biochar is subjected to a series of aging reactions, including oxidation, hydration–dehydration processes, biological colonization, mineral precipitation, and sorption of organic and inorganic compounds in dissolved forms after it is applied [11]. Such changes may affect functional groups on the surface, porosity, surface charge, and aggregation, and thus influence nutrient retention, pollutant adsorption, and biochar–soil interactions [97]. In certain cases, such as an increase in the amount of oxygenated functional groups and cation-exchange capacities, aging makes biochar better in terms of

nutrient retention and pollutant sorption; in other cases, pore blockage, breakdown, or hydrophobicity change due to aging hinders further reactions. Biochar needs to be treated not as a static material with fixed characteristics but as a dynamic one.

It is this dynamism that accounts for the fact that laboratory observations do not always match field situations. Batch sorption studies, incubation tests, and greenhouses provide useful insights into the mechanisms involved, but simplify the environmental factors controlling long-term biochar functionality in natural soils. In field conditions, there is variation in moisture regimes, varying temperatures, microbial succession, root exudates, organic solutes, colloids, wet/dry cycles, and freeze/thaw cycles, all of which affect desorption of the contaminant and nutrient cycling and aging of the structure [98]. Therefore, strong immobilization of contaminants or nutrient retention observed in laboratory studies is likely to overestimate the longevity of the effect in field conditions, whereas laboratory phytotoxicity or release of a contaminant within a few hours after biochar manufacturing is likely to underestimate the stabilizing effect of weathering after biochar application.

The mobility of contaminants and their plant uptake in biochar-amended soil are influenced by the same factors that govern immobilization and release. Contaminant and metal mobility may decrease due to biochar's higher sorption capacity, increased soil pH, precipitation/complexation, and entrapment in biochar pores. Meanwhile, biochar may increase the mobility of some elements because of the dissipation of organic carbon, the release of fine particles, and the dissolution of ash in biochar, which increases mobility in the soil matrix [98]. Plant response to such treatment depends not only on the contaminant load in the biochar itself but also on how biochar affects rhizosphere chemistry, nutrients, salinity, and biological activity in the soil [99]. Increased metal immobilization and improved plant growth are typical results of biochar treatment due to beneficial changes in the soil [100], while the negative consequences of using newly prepared and improperly stabilized biochar may include emissions of phytotoxic volatiles, salt load, high pH, and increased contaminant mobility [101].

In terms of its long-term safety, the important thing to consider when assessing a biochar is whether it will behave properly over a period of continued use. This means that a biochar used for agricultural applications should also undergo assessment based on its life cycle, in which, apart from the levels of contaminants it carries initially, the following factors must be considered:

- Changes in contaminant availability associated with aging;
- Cumulative loading of soil with contaminants;
- Persistence of sorbed contaminants;
- Possible latent effects on the soil microbiota and plants.

This kind of analysis becomes particularly necessary when dealing with biosolid-based biochar, in which case, the recycling benefits associated with the technology should be carefully weighed against the risks of concentrating trace metals and other substances that may become mobile during prolonged use. The safe-by-design development of this technology for agricultural purposes should include assessments of the feedstock and the reactors used in biochar manufacturing, post-production processing, certification compliance, and evaluation of its performance in the field under real environmental conditions.

7. Certification Standards, Safe-by-Design Biochar Production, and Future Research Directions

The widespread adoption of biochar in agricultural and environmental remediation contexts has resulted in the need for certification standards to differentiate between agronomically useful biochar and those that carry potentially hazardous contaminants. Certification programs such as the IBI and the EBC have been critical in ensuring biochar quality

by defining appropriate raw material sources, setting threshold levels for contaminants such as PAHs and heavy metals, and mandating testing of biochar products before land application. Such frameworks have increased transparency and standardization within the biochar industry and created the basis for safety criteria for biochar utilization. However, the limitations of certification programs are evident in their nature: these standards use the threshold concentration approach, which does not account for contaminant speciation, time-related changes in contaminant availability, colloid-aided mobilization, or synergistic effects among contaminants. The limiting value for PAHs in biochars was initially set by the International Biochar Initiative (IBI) at 6–20 mg/kg, however it was increased from 20 mg/kg to 300 mg/kg, But now the European Biochar Certificate (EBC) set the limit at $6.0 + 2.2 \text{ g t}^{-1}$ dry matter (DM) for EBC-Agro and $4 \pm 2 \text{ g t}^{-1}$ DM for EBC-Agro Organic biochar's [102]. In summary, meeting IBI or EBC standards is a necessary starting point in using biochar sustainably [94,103].

This limitation underscores the need for a safe-by-design approach in which contaminant control is embedded throughout the biochar production chain rather than assessed only after the material has been produced. Safe-by-design biochar production begins with feedstock screening to avoid inputs with excessive burdens of trace metals, salts, or problematic organic residues, particularly when using sludge-, manure-, or waste-derived materials [104]. It also requires reactor configurations and operating conditions that minimize contaminant generation by controlling oxygen ingress, vapor residence time, temperature distribution, and cooling behavior, while preserving the functional properties needed for soil amendment or pollutant sorption. In this context, the design challenge is inherently multi-objective: production systems must balance carbon yield, nutrient retention, porosity, liming potential, contaminant minimization, and energy efficiency rather than optimizing a single performance metric. Post-production conditioning, contaminant testing, and fit-for-purpose application strategies are equally important because even biochar that satisfies threshold criteria may behave differently depending on soil properties, application rate, and the sensitivity of the receiving environment. Safe biochar development should therefore be framed as an integrated feedstock–reactor–product–application system rather than as a purely analytical exercise in contaminant measurement [105,106].

Despite substantial progress, the literature still contains important inconsistencies and unresolved questions that limit the development of predictive, transferable design rules for safe biochar production. Quantitative comparisons among studies remain difficult because reactor type, vapor residence time, cooling conditions, analytical methods, and feedstock composition are often confounded or incompletely reported. This is particularly evident for PAHs, where contradictory findings persist regarding the relative importance of temperature, feedstock aromaticity, and vapor re-condensation in determining final contaminant loads. Similar gaps remain for heavy metals and persistent free radicals, especially with respect to how pyrolysis conditions alter contaminant speciation, radical stability, and long-term ecological relevance after soil application. Another persistent weakness is the limited integration of laboratory and field evidence: many studies quantify contaminant concentrations immediately after production but do not evaluate how aging, microbial processing, colloidal transport, or repeated application influence long-term mobility and exposure. These limitations indicate that current knowledge is still stronger in identifying risk factors than in predicting contaminant behavior across diverse production and environmental scenarios.

Future research should focus on moving beyond descriptive studies toward a more forward-looking, systems-based evaluation of biochar safety. Key research directions include developing standardized reporting guidelines for reactor design, vapor handling, and cooling conditions; conducting quantitative cross-study analyses of PAH and metal

contents across feedstocks and biochars produced under different systems; and conducting field studies to clarify how contaminant transformation, bioavailability, plant bioaccumulation, and microbial behavior relate to aging. There is also a need to develop multi-objective optimization methods that identify operating conditions that maximize agronomic effectiveness, carbon stability, and contaminant reduction, possibly using machine learning and hybrid mechanistic-data-driven approaches based on well-analyzed production data. Lastly, life-cycle and techno-economic aspects should be integral to biochar safety assessments, given the need to balance biochar's environmental benefits, such as waste utilization, carbon storage, and soil remediation, against the costs and burdens of contaminant control, energy, and material use incurred by biochar production. To develop biochar as a sustainable technology, it is necessary to consider both certification requirements and the safe-by-design approach that would integrate production chemistry, reactor.

8. Conclusions

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, feedstock, 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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