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Review

Biochar and Sustainable Crop Performance: A Synoptical Review of Its Properties, Agronomic Potential and Constraints

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Abstract

Biochar has emerged as one of the most promising nature-based strategies for improving soil quality, enhancing crop productivity and supporting climate-smart agriculture. However, the agronomic performance of biochar remains highly variable because its effects are governed by complex interactions among feedstock characteristics, pyrolysis conditions, soil properties and management practices. This review synthesizes recent advances in biochar research (2019–2026), examining how production variables determine biochar physicochemical properties and how these properties subsequently influence soil functioning, plant performance and long-term agricultural sustainability. The review integrates evidence on feedstock selection, pyrolysis technologies, biochar modification strategies and the relationships between biochar properties and soil physical, chemical and biological processes. Particular attention is given to crop productivity, nutrient use efficiency, stress mitigation, contaminant immobilization, greenhouse gas mitigation and long-term soil resilience. Across the literature, the most consistent agronomic benefits were observed when biochar was applied to degraded or resource-limited soils and integrated with complementary management practices, whereas responses were often limited under fertile soils, low application rates or short experimental periods. Rather than identifying a universally superior biochar, the evidence indicates that agronomic performance depends on matching biochar characteristics to specific production objectives and environmental conditions. Based on these findings, this review proposes a transition from generalized biochar application towards optimized deployment strategies supported by standardized characterization, long-term multi-site validation and integrated environmental and economic assessments. This synthesis provides a comprehensive framework for guiding future research and facilitating the effective implementation of biochar within sustainable and regenerative agricultural systems.

Keywords: biochar; crop-productivity; regenerative agriculture; soil amendment; sustainability

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1. Introduction

Global population growth and the intensification of food production, along with climate change, are placing unprecedented pressure on natural resources, particularly soil, water, and biodiversity [1–3]. At the same time, many conventional agricultural practices, characterized by intensive tillage, excessive agrochemical inputs, and inefficient resource management, have contributed to widespread soil degradation, declining fertility, and increased environmental vulnerability [3–5]. These challenges highlight the urgent need to transition towards more sustainable agricultural systems capable of maintaining productivity while preserving ecosystem integrity.

Regenerative agricultural practices have emerged as a promising pathway toward restoring soil health while maintaining productive landscapes. Broadly defined, regenerative agriculture encompasses management strategies that rebuild soil organic matter, enhance biodiversity, and strengthen ecosystem functions rather than merely sustaining them [6,7]. Within this framework, biochar has attracted growing attention as a multifunctional soil amendment [8]. Produced through the pyrolysis of biomass under limited oxygen conditions, biochar possesses unique physicochemical properties that can influence soil structure, nutrient dynamics, water retention, and carbon sequestration [4,9–12]. Although the concept is not new (in reference to the ancient amazonian *Terra Preta do Índio* soils created through the long-term incorporation of charred organic materials), biochar has recently earned renewed scientific interest as a tool for climate-smart agriculture [13–15]. However, despite its promising attributes, important uncertainties remain regarding its agronomic performance, economic feasibility, and long-term environmental implications [16–18].

Despite the comprehensive body of knowledge currently available on biochar production technologies, physicochemical properties, environmental applications, carbon sequestration, greenhouse gas mitigation, or specific agronomic responses, these topics are frequently addressed independently. Comparatively fewer reviews integrate the entire sequence linking biomass feedstock and production parameters to biochar properties, subsequent modifications in soil physical, chemical and biological processes, crop responses, and long-term agronomic sustainability. Consequently, although the individual mechanisms underlying biochar behaviour are relatively well documented, the interactions among these processes, and their role in explaining the context-dependent performance of biochar across agricultural systems, remain sparsely synthesized. Bridging these different levels of evidence is essential for translating experimental findings into practical recommendations capable of supporting site-specific biochar management.

Accordingly, this review adopts an integrated and context-oriented perspective to examine how biochar production parameters determine its physicochemical properties and how these properties subsequently influence soil processes, plant responses, and agronomic sustainability. By synthesizing evidence published between 2019 and early 2026, this review evaluates recent advances regarding biochar production, modification strategies, physicochemical characteristics, soil physical, chemical and biological responses, crop productivity, environmental sustainability, and current limitations. Particular emphasis is placed on identifying the mechanisms responsible for the highly variable agronomic performance of biochar reported in the literature, highlighting current knowledge gaps, discussing the principal constraints limiting large-scale implementation, and proposing a practical framework for the development of more predictable, efficient, and context-specific biochar management strategies. To achieve this objective, the review is organized into five interconnected themes covering biochar production and modification, physicochemical properties, soil and crop responses, sustainability implications, and the major limitations and future research needs associated with its agricultural application.

2. Materials and Methods

2.1. Literature Search Strategy

This review was conducted using a structured narrative approach to synthesize recent advances regarding the production, physicochemical properties, agronomic applications, sustainability implications, and limitations of biochar in agricultural systems. A comprehensive literature search was performed between January and February 2026 using the scientific databases Scopus, Web of Science, ScienceDirect, and Google Scholar.

The search strategy combined keywords related to biochar production and agricultural applications, including "biochar", "pyrolysis", "feedstock", "soil amendment", "soil fertility", "soil microbiology", "soil hydraulics", "crop productivity", "water retention", "carbon sequestration", "greenhouse gas emissions", "circular bioeconomy", "regenerative agriculture", and related terms. Boolean operators (AND/OR) were used to refine the search and improve retrieval accuracy.

2.2. Eligibility Criteria

The review primarily included peer-reviewed articles published in English between 2019 and early 2026, together with a limited number of earlier publications considered essential for providing historical context or describing fundamental biochar concepts. Original research articles, review papers, and meta-analyses focusing on agricultural applications of biochar were considered eligible.

Publications unrelated to agricultural systems, conference abstracts, editorials, duplicate records, and studies providing insufficient methodological information or limited scientific relevance to the objectives of this review were excluded. The detailed eligibility criteria are shown below in Table 1.

Table 1. Eligibility criteria for the review.

Inclusion Criteria	Exclusion Criteria
Peer-reviewed original research articles, systematic reviews and meta-analyses.	Non-peer-reviewed publications (conference abstracts, editorials, theses and reports).
Publications in English, published primarily between 2019 and early 2026.	Publications outside the defined scope or superseded by more recent evidence.
Studies focusing on biochar production, properties, soil–plant interactions, agronomic performance, sustainability and environmental impacts.	Studies unrelated to agricultural biochar applications or providing insufficient methodological detail.

2.3. Study Selection and Data Synthesis

The literature search resulted in the compilation of a bibliographic database containing 187 scientific publications. Following title, abstract, and full-text evaluation according to their scientific relevance and consistency with the objectives of the review, 124 scientific publications were selected for inclusion in the final manuscript.

Information extracted from each study included biomass feedstock, production technology, pyrolysis conditions, physicochemical properties, modification strategies, soil characteristics, crop species, agronomic responses, environmental impacts, and reported limitations.

2.4. Data Analysis

Owing to the considerable heterogeneity among experimental designs, biochar feedstocks, production conditions, soil types, climatic conditions, crop species, application rates, and response variables, a quantitative meta-analysis was not considered appropriate. Therefore, the available evidence was synthesized using a structured narrative approach, emphasizing the comparison of reported outcomes and the discussion of the mechanisms underlying biochar performance.

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3. Biochar Production, Properties, Agronomic Applications, Challenges and Limitations

The following content is structured into three main sections. The first examines biochar production pathways and the physicochemical properties of the resulting materials. The second synthesizes the agronomic implications of biochar application, encompassing its effects on soil physical, chemical, and biological processes, as well as crop performance, nutrient dynamics and sustainability. Finally, the Section 3 of this review focuses on challenges and limitations surrounding biochar use in agricultural settings.

3.1. Biochar: Production and Properties

Biochar is a carbon-rich material produced through the thermochemical conversion of biomass under limited or absent oxygen conditions, at high temperatures, usually in a process referred to as pyrolysis [15,19–22]. This process promotes the transformation of organic feedstocks into a relatively stable, aromatic carbon structure while retaining varying proportions of mineral constituents [22].

The agronomic performance of biochar is intrinsically linked to its production parameters and compositional characteristics. Feedstock type, pyrolysis temperature, heating rate, and residence time significantly influence its physicochemical properties, including surface area, porosity, pH, cation exchange capacity, and carbon stability. Consequently, controlling these variables is critical to tailoring biochar functionality for specific soil and crop systems. Figure 1 presents a conceptual diagram illustrating the various factors influencing biochar production and properties and, consequently, its agronomic effects in soil–plant systems.

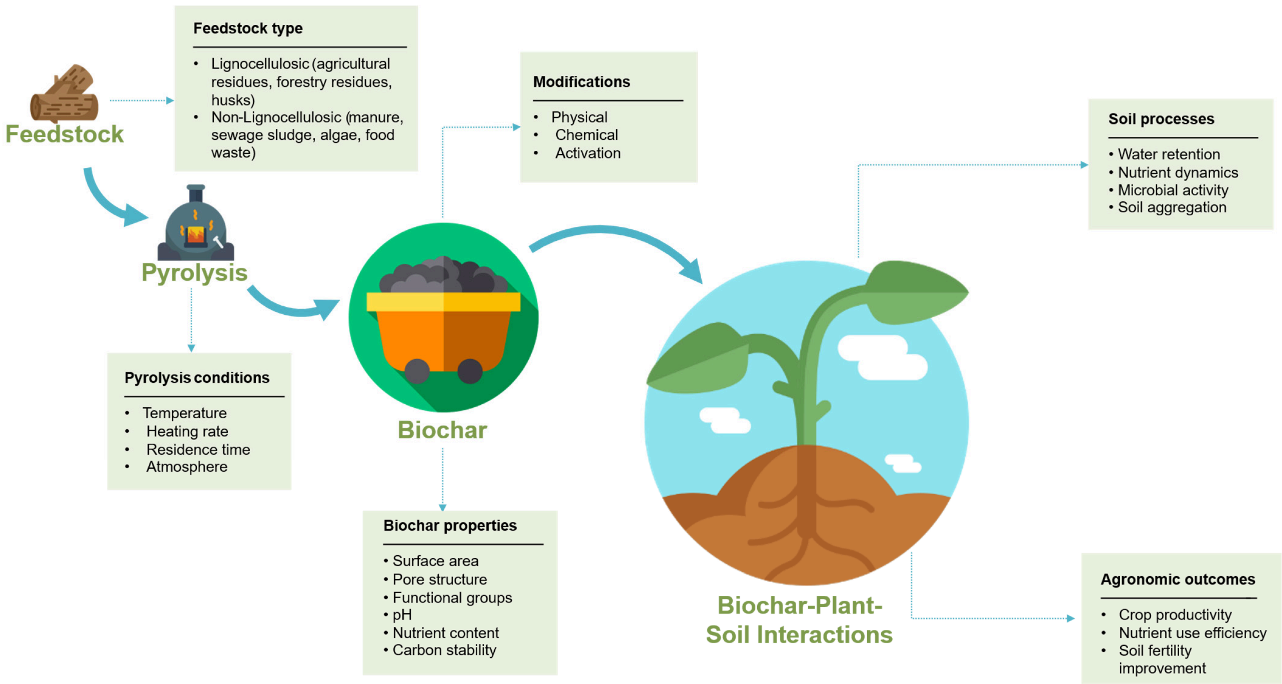

Figure 1. Key factors influencing biochar properties and their implications for soil and crop performance. Biochar properties are primarily determined by the type of feedstock (lignocellulosic or non-lignocellulosic biomass), pyrolysis operating conditions (temperature, heating rate, residence time and atmosphere), and optional post-production modification strategies (physical, chemical or activation treatments). These production variables define key physicochemical characteristics of biochar, including surface area, pore structure, functional groups, pH, nutrient content and carbon stability. Once incorporated into soil, these properties regulate biochar–soil–plant interactions by influencing fundamental soil processes such as water retention, nutrient cycling, microbial activity and soil aggregation. (Icons designed by Magnific, www.magnific.com (accessed on 11 March 2026).

3.1.1. Production

Feedstock

One of the first aspects to consider in biochar production is the type of feedstock, as it is one of the main determinants of the material's physical, chemical and functional properties. Ideally, biomass should exhibit low moisture content, high lignin content, low ash content and a high calorific value, since these factors affect the efficiency and yield of the pyrolysis process [20]. Biomass used for biochar production may originate from diverse sources and is generally classified as lignocellulosic (agricultural residues, forestry residues, husks, sawdust) or non-lignocellulosic (manure, sewage sludge, algae, food waste) [23,24].

In terms of composition, biomass contains three main organic components—cellulose, hemicellulose and lignin—along with inorganic mineral matter. Thermal decomposition of these components occurs at different temperature ranges during pyrolysis, influencing product yield and distribution [22,25]. Hemicellulose, cellulose, and lignin decompose at distinct temperature ranges that shape their pyrolytic behaviour. Hemicellulose degrades first, between 220 and 315 °C, yielding mainly low-molecular-weight volatiles that contribute to bio-oil and syngas formation. Cellulose decomposes next, within 315–400 °C, producing predominantly volatile compounds through depolymerization and rearrangement reactions, with relatively limited biochar generation. In contrast, lignin undergoes the broadest and most gradual decomposition, spanning 160–900 °C, driven by free-radical mechanisms and resulting in substantial biochar formation alongside phenolic bio-oil precursors [22]. Biomass with higher lignin content and lower cellulose content is preferred for producing biochar with higher fixed carbon content and long-term stability [20,26,27]. Additionally, the presence of minerals in biomass can act as catalysts, affecting both thermal decomposition and the properties of the final biochar [25].

Moisture content is another critical factor. For fast pyrolysis processes, moisture levels below 10% are recommended to minimize energy costs. In contrast, slow pyrolysis or pressurized processes can accommodate biomass with 40–60% moisture, although with a greater impact on energy efficiency [23]. Kumar and Bhattacharya [20] further note that biomass moisture content should be below 30%, ideally achieved through solar drying, to reduce energy consumption and improve thermal efficiency.

The physicochemical characteristics of biochar are strongly determined by the nature of the precursor biomass. Agricultural residues, agro-industrial by-products, marine biomass, and organic wastes exhibit distinct structural and elemental compositions that translate into different functional behaviours in soil systems. For instance, devolatilized agricultural pod residues produced stable carbon-rich biochar with enhanced surface area and structural ordering, although their properties varied significantly across feedstocks [28]. Similarly, maize cob biochar demonstrated increasing carbon content and porosity with rising pyrolysis temperatures, reflecting the progressive transformation of lignocellulosic material into more aromatic carbon structures [29]. Marine biomass feedstocks such as *Posidonia oceanica*, *Halidrys siliquosa*, and *Ulva lactuca* produced biochar rich in essential plant nutrients, including N, P, K, Ca, Mg, and micronutrients, with elemental composition influenced more strongly by temperature than holding time [30]. These findings highlight the dual function of certain feedstocks, combining carbon stabilization with nutrient supply potential. Pandey et al. [23] mentioned that straw-derived biochar typically exhibits a higher pH (around 9.5) and higher potassium content than wood-derived biochar; in addition, residues such as rice husk or peanut shells tend to yield higher biochar production.

Co-pyrolysis approaches also demonstrate feedstock synergy. Basika et al. [31] showed that combining fecal sludge and rice husks (50:50 ratio) at 550 °C produced biochar with enhanced surface area (62.7 $m^2\ g^{-1}$), improved pore volume, and favourable functional group profiles, suggesting that strategic blending can optimize material performance. A summary of main feedstock categories and their key characteristics is presented below in Table 2.

Table 2. Comparative table of different feedstock categories and their characteristics.

Feedstock Category	Characteristics of Resulting Biochar	Examples
Woody biomass	High fixed carbon, high aromaticity, low ash content, relatively low nutrient concentration	Wood chips, sawdust, forestry residues [20,23,29]
Agricultural residues	Moderate to high carbon content, moderate ash content, alkaline pH, relatively high K concentration	Straw, maize cobs, rice husks, peanut shells, pod residues [23,28,29]
Animal manure	High ash content, high nutrient concentration (N, P, K), high electrical conductivity, alkaline pH	Poultry litter, cattle manure [23,24]
Sewage sludge/fecal sludge	Rich in nutrients and mineral phases; relatively high surface functionality	Sewage sludge, fecal sludge [24,31]
Marine biomass	Rich in macro- and micronutrients (N, P, K, Ca, Mg); composition strongly influenced by pyrolysis temperature	*Posidonia oceanica*, *Halidrys siliquosa*, *Ulva lactuca* [30]
Co-pyrolyzed feedstocks	Tailored physicochemical properties through feedstock blending; increased surface area and pore volume	Rice husk + fecal sludge (50:50) [31]

Beyond agronomic properties, feedstock selection carries environmental and socioeconomic implications. The use of organic residues for biochar production not only reduces solid waste but also valorizes agricultural by-products and strengthens overall waste-management practices, thereby aligning with several Sustainable Development Goals (SDGs) [20].

Processes

Biochar production can be carried out through different thermochemical conversion processes, such as combustion, gasification, torrefaction, flash carbonization, hydrothermal carbonization and pyrolysis. The latter is the most widely used process for producing stable biochar and is considered technically and environmentally more suitable [22,23,32].

(a) Pyrolysis

Pyrolysis is a thermochemical conversion process in which biomass is heated in an inert atmosphere (absence of oxygen), leading to its decomposition into three main fractions: biochar (solid), bio-oil (liquid) and synthesis gas (syngas). Biomass undergoes thermal depolymerization reactions when exposed to temperatures between 300 and 900 °C, resulting in the breakdown of organic chains and the formation of more stable compounds [22,25].

The proportion of products obtained depends on variables such as pyrolysis temperature (°C), heating rate (°C s^{-1} or °C min^{-1}), residence time (s or min), and biomass characteristics such as moisture content, lignocellulosic composition and particle size. For example, higher temperatures tend to favour the formation of gases and liquids, whereas moderate temperatures combined with longer residence times result in a higher proportion of biochar with elevated fixed carbon content [20,22,25].

From a physical standpoint, pyrolysis is an endothermic process requiring external heat input. However, part of the syngas generated can be recirculated to thermally sustain the reactor, improving the overall energy efficiency. Biomass conversion depends on the structure of its lignocellulosic constituents and the way they fragment during heating. The vapours produced are typically directed through cyclones and condensers, which separate the liquid fraction (bio-oil) from the non-condensable gases, which can be reused as an energy source [25].

Pyrolysis can be broadly classified into three to four operational regimes: slow, intermediate, fast and flash pyrolysis, which differ primarily in heating rate and residence time, while their temperature ranges partially overlap. These operational parameters determine the relative proportions of biochar, bio-oil and syngas, as well as the physicochemical characteristics of the resulting biochar [22,26,33,34].

Among these, slow pyrolysis remains the dominant technology for agricultural biochar production. It is typically performed at moderate temperatures (approximately 300–700 °C) under relatively low heating rates and long residence times (from minutes to several hours or even days), conditions that promote secondary carbonization reactions and maximize solid carbon recovery. Consequently, slow pyrolysis generally produces the highest biochar yields (≈30–45%), characterized by elevated fixed carbon content, greater aromaticity and enhanced long-term stability, making it particularly suitable for soil amendment and carbon sequestration [22,23,26,33].

As heating rate increases and residence time decreases, thermal decomposition increasingly favours volatilization reactions over char formation. Intermediate pyrolysis represents a transitional regime, producing relatively balanced proportions of biochar and bio-oil, whereas fast pyrolysis is specifically designed to maximize liquid fuel production. Operating at temperatures generally above 500 °C, with very high heating rates and residence times of only a few seconds, fast pyrolysis typically yields around 60% bio-oil, 20% biochar and 20% syngas, with the resulting biochar generally exhibiting lower yield and recalcitrance than that produced by slow pyrolysis [33,34].

Flash pyrolysis follows the same principle as fast pyrolysis but represents its most extreme operational configuration. It employs ultra-high heating rates (>1000 °C s^{-1}), residence times below 10 s and finely milled biomass to maximize heat transfer and almost instantaneous volatilization. As a result, flash pyrolysis further increases liquid product recovery while minimizing biochar formation, making it primarily suitable for biofuel production rather than agricultural biochar applications [23,34,35].

Overall, the transition from slow to flash pyrolysis reflects a progressive shift from maximizing biochar production towards maximizing bio-oil and syngas generation, illustrating the inherent trade-off between carbon sequestration potential and energy recovery.

Still regarding pyrolysis, temperature remains one of the most critical determinants of biochar properties. Across multiple studies, increasing pyrolysis temperature consistently reduced biochar yield but enhanced aromaticity, structural stability, and carbon condensation.

In maize cob biochar, yield declined from 34.3% at 300 °C to 22% at 500 °C, while fixed carbon content increased from 47% to 57%, accompanied by substantial increases in surface area and porosity [29]. Similar trends were reported for agave-derived biochar, where higher temperatures (550–700 °C) significantly reduced H/C and O/C ratios, indicating greater aromaticity and long-term carbon stability [36]. However, these improvements occurred alongside reduced mass yield, illustrating the trade-off between production efficiency and carbon recalcitrance. Atmospheric conditions during pyrolysis further influence structural development.

Gomes da Silva et al. [36] demonstrated that a CO_2 atmosphere enhanced surface area and porosity relative to N_2, suggesting that controlled oxidative environments can modify pore architecture without compromising stability.

Moreover, high-temperature treatment can substantially reduce contaminant content in certain feedstocks. In cocoa pod husk biochar, pyrolysis at ≥700 °C reduced Cd concentrations by over 90%, while also increasing adsorption capacity (qm = 21.58 mg g^{-1}), highlighting the dual role of thermal treatment in detoxification and sorptive functionality [37]. Table 3 summarizes the relationship between pyrolysis temperature parameters and the biochar properties and their consequent agronomical effect.

Table 3. Influence of pyrolysis temperature on biochar profile.

Pyrolysis Parameter	Outcomes	Biochar Properties	Implications for Soil and Crop Performance	Source
Increasing temperature (300–500 °C)	Biochar yield decreased from 34.3% to 22%, while fixed carbon increased from 47% to 57%	Greater aromaticity, higher carbon condensation, increased structural stability, larger surface area and porosity	Enhanced long-term SOC stabilization, improved aggregate formation, greater water retention and nutrient adsorption, although with reduced production yield	[29]
Higher pyrolysis temperatures (550–700 °C)	Progressive decrease in H/C and O/C ratios	Greater aromaticity and carbon recalcitrance	Increased long-term persistence of biochar in soil and greater carbon sequestration potential, but lower biochar production efficiency	[35]
CO_2 atmosphere (vs. N_2)	Increased surface area and porosity	More developed pore architecture without compromising structural stability	Enhanced adsorption capacity and potentially improved nutrient retention and soil amendment performance	[35]
High-temperature pyrolysis (≥700 °C)	Cd concentration reduced by >90% and adsorption capacity increased (qm = 21.58 mg g^{-1})	Lower contaminant content and enhanced sorptive functionality	Reduced contaminant bioavailability, safer application of biochar derived from contaminated biomass and greater potential for soil remediation	[36]

(b) Other Processes

In addition to pyrolysis, several other processes can be used for biochar production, each with its own specific characteristics (Figure 2) [24,33–35]:

- **Gasification (500–1200 °C)—**produces mainly syngas, with a low biochar yield (~10%).
- **Torrefaction (200–300 °C)—**a mild pretreatment of biomass, with limited impact on biochar production.
- **Flash Carbonization (350–650 °C)—**a rapid, pressurized process that generates a balanced proportion of biochar and gases.
- **Hydrothermal Carbonization (800–1200 °C)—**used for wet biomass; produces hydrochar, which is not directly comparable to pyrolysis-derived biochar.

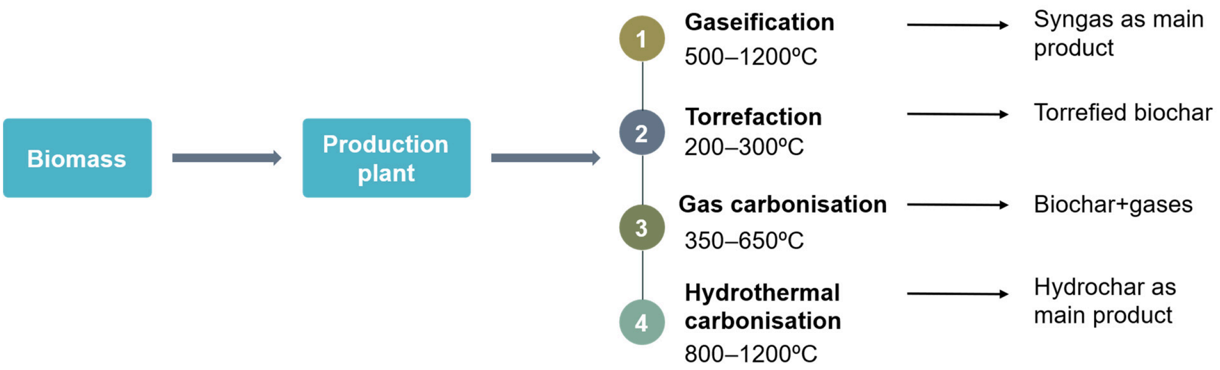

Figure 2. Schematic representation of the main biomass-to-biochar production pathways. Lignocellulosic biomass is converted into biochar through different thermochemical technologies (gasification, torrefaction, flash carbonization, and hydrothermal carbonization), each characterized by specific operating conditions that influence the physicochemical properties and potential agricultural applications of the resulting biochar.

Modifications

Although pyrolysis-derived biochar already exhibits valuable properties, it can be further modified to enhance its effectiveness, particularly in terms of surface area and pore development (often achieved through activation techniques), surface functional groups, adsorption capacity, and chemical reactivity. Biochar modification can involve physical or chemical treatments, with chemical approaches being the most widely applied [32,38,39].

(a) Physical Modifications

Particle size represents a practical post-production parameter influencing soil–biochar interactions. Field evidence indicates that finer biochar fractions (<2 mm) can improve nitrogen uptake, nutrient use efficiency, and grain yield in rotation systems, particularly when combined with biofertilizers [40]. However, particle size also affects soil aeration and moisture dynamics, with optimized size distributions influencing water–oxygen balance and delaying senescence under drip irrigation systems [41].

At the nanoscale, biochar modification can significantly enhance contaminant immobilization capacity. Raczkiewicz et al. [42] reported stronger polycyclic aromatic hydrocarbons (PAH) immobilization and improved soil health indicators using nanoscale biochar compared to conventional forms, demonstrating the importance of surface reactivity and particle size in remediation contexts.

Additionally, digestion-mediated modification offers an unconventional pathway for biochar ageing and stabilization. Walz et al. [43] demonstrated that 70–90% of biochar fed to dairy cattle was recovered in manure, retaining highly condensed aromatic structures ($H/C \approx 0.22$; $O/C \approx 0.05$) and ~97% of the persistent carbon matrix. These findings suggest that manure-mediated application may preserve biochar stability and contribute to long-term carbon sequestration.

(b) Chemical Modification

Acid modifications primarily aim to remove impurities such as metals and to introduce acidic functional groups (carboxylic, phenolic, lactonic) on the biochar surface. Different acids, such as HCl, HNO_3, H_2SO_4 or H_3PO_4, produce variable effects on surface area and functional composition, depending on their concentration, the biomass type and the treatment conditions. Some combinations, such as sulfuric acid with oxalic acid, have shown substantial increases in surface area, whereas others may reduce it [33,38,39].

Alkaline modifications are typically performed using potassium hydroxide (KOH) or sodium hydroxide (NaOH), with the main objective of increasing surface area and introducing oxygen-containing groups such as hydroxyls and carboxyls. Although generally effective, results vary depending on the biomass type and the biochar production method. For example, NaOH has been shown to be more cost-effective and, in some cases, more efficient than KOH. The ratio between biochar mass and alkaline reagent directly influences the outcome [33,39,44].

On the other hand, oxidizing agents such as hydrogen peroxide (H_2O_2) or potassium permanganate ($KMnO_4$) are used to introduce oxygen-containing groups on the biochar surface, increasing affinity for certain pollutants. However, effectiveness depends on the nature of the target contaminant, and trade-offs may arise between functionalization and adsorption capacity. Additionally, reagent cost and post-treatment requirements limit large-scale application [32].

Despite the clear advantages of biochar modification in enhancing adsorption capacity, nutrient retention and pollutant immobilization, these benefits are accompanied by important agronomic trade-offs that may limit large-scale agricultural adoption. Most modification techniques require additional processing steps, chemical reagents or energy-intensive treatments, increasing production costs compared with pristine biochar [38,39]. Physical activation methods, such as steam or gas treatment, improve porosity and surface area but require high energy inputs, whereas carbon-based modifiers (e.g., graphene) remain economically prohibitive for most agricultural applications. Chemical modifications using acids, alkalis or oxidizing agents further increase process complexity because residual solutions require appropriate treatment and disposal to prevent secondary environmental contamination. Likewise, metal- or metal oxide-modified biochars raise concerns regarding the potential release of metal ions into soil, highlighting the need to improve the long-term stability of these materials before widespread field application [32]. From an agronomic perspective, these additional production costs reduce the economic feasibility of biochar-based products, particularly for small- and medium-scale farming systems, where adoption is strongly influenced by input costs [45]. Furthermore, although modified biochars frequently stimulate microbial activity by improving soil habitat and nutrient availability, their long-term effects on soil microbial communities and soil ecological functioning remain insufficiently understood [46]. Consequently, future research should focus not only on maximizing modification efficiency but also on developing cost-effective, scalable and environmentally safe modification strategies that maintain agronomic benefits under realistic field conditions.

Comparing the techniques, alkaline modification tends to increase surface aromaticity and the nitrogen-to-carbon ratio, making the biochar more basic and less hydrophilic. Oxidizing agents, in contrast, predominantly introduce carboxylic groups. The choice of modification method must consider the intended application of the biochar, operational costs, waste generated during treatment and the desired effects in terms of adsorption, nutrient retention or catalytic activity [32].

(c) Activation

Activation is a specific engineering strategy used to enhance the structural and surface properties of biochar by increasing its porosity, surface area, and density of reactive functional groups. This process can be achieved through physical activation, typically involving high-temperature treatment with oxidizing gases such as steam or CO_2, or chemical activation using agents such as KOH, $ZnCl_2$, or H_3PO_4 that promote pore development and surface functionalization [44]. In addition to classical methods, several alternative approaches have emerged, such as UV radiation activation and magnetic modification. Exposure to UV radiation, particularly UV-A (315–380 nm), induces oxidation on the biochar surface, forming oxygen-containing functional groups and increasing surface area [23]. Activated biochar generally exhibits improved adsorption capacity and greater reactivity, which can enhance nutrient retention and contaminant immobilization in soils. However, despite these potential benefits, activation techniques are more commonly applied in environmental remediation and material science, and remain relatively uncommon in agronomic applications due to their higher processing complexity and cost compared to conventional biochar production [44].

3.1.2. Properties

Collectively, the reviewed studies indicate that key physicochemical properties, namely surface area, pore volume, aromaticity, pH, nutrient content, and elemental ratios, are tightly regulated by production parameters.

Physical Properties

(a) **Specific Surface Area—**Biochar typically exhibits a surface area ranging from 1.5 to 500 m^2/g. This generally increases with higher pyrolysis temperatures, as the release of volatiles and tars opens internal pores within the carbon matrix. However, beyond a critical temperature threshold, micropore collapse may occur, reducing total surface area [19,23,39].
(b) **Water Holding Capacity—**Water-holding capacity is governed by the combined effects of pore structure and surface chemistry. Increasing pyrolysis temperature generally removes tar residues and improves pore accessibility, favouring water storage within the biochar matrix [47,48]. However, higher temperatures also reduce oxygen- and nitrogen-containing functional groups while increasing aromaticity, thereby decreasing surface wettability [19,49]. Consequently, the overall effect of pyrolysis temperature on water-holding capacity depends on the balance between enhanced pore development and the loss of hydrophilic surface functionalities, as well as on feedstock characteristics.
(c) **Structural Stability—**Due to its high aromatic carbon content, low solubility and resistance to physical, chemical and biological degradation, biochar is highly stable and can persist in soils for long periods. This long-term persistence contributes to carbon sequestration and improved soil quality [20,23,39].
(d) **Porosity and Density—**Biochar's low bulk density and highly porous structure enhance its capacity to retain water and nutrients, particularly in sandy soils. Studies indicate that biochar application can reduce soil bulk density by 3–31% and increase porosity by 14–64%. These effects improve plant water use efficiency and nutrient uptake, promoting more sustainable plant growth [20,23,39].

Chemical Properties

(a) **pH—**Biochar is generally alkaline due to the presence of ash, carbonates and phosphates formed during pyrolysis. Its pH tends to increase with higher carbonization temperatures as acidic functional groups (such as carboxyls) decompose and organic acids volatilize. For example, poultry manure-derived biochar typically exhibits a higher pH than biochar produced from woody biomass [19]. Thus, biochar pH increases with pyrolysis temperature, reflecting the decomposition of acidic functional groups and the volatilization of organic acids [20,39].
(b) **Functional Groups—**The surface of biochar is rich in functional groups such as carboxyl, hydroxyl and carbonyl, particularly in biochar produced at lower temperatures. These groups confer adsorption capacity, buffering ability and ion exchange properties. As pyrolysis temperature increases, the number of oxygen-containing functional groups tends to decrease, being replaced by more stable and alkaline groups [19,39].
(c) **Cation Exchange Capacity (CEC)—**Biochar CEC is closely linked to the presence of oxygen-containing functional groups. At moderate temperatures, retention of these

groups can increase CEC, whereas higher pyrolysis temperatures reduce CEC by degrading them. However, the increased presence of alkaline elements such as K, Ca and Mg at higher temperatures may partially compensate for this reduction [19,20,39].

A summarized table is presented below encapsulating the key aspects of biochar physicochemical properties at play in the agronomical context (Table 4).

Table 4. Summary of the main physical and chemical properties of biochar.

Physical Properties	Chemical Properties
Specific surface area—1.5–500 m^2 g^{-1}; generally increases with pyrolysis temperature until pore collapse occurs.	pH—Typically alkaline; increases with pyrolysis temperature and ash content.
Water-holding capacity—Governed by pore structure and surface chemistry; strongly influenced by feedstock and pyrolysis conditions.	Functional groups—Carboxyl, hydroxyl and carbonyl groups regulate adsorption, buffering and ion exchange.
Structural stability—High aromatic carbon content provides long-term persistence and carbon sequestration potential.	Cation exchange capacity (CEC)—Controlled by oxygen-containing functional groups and alkaline mineral content.
Porosity and bulk density—High porosity and low density improve aeration, infiltration and water storage.	Nutrient content—Feedstock-dependent concentrations of K, Ca, Mg, P and other mineral elements contribute to soil fertility.

The physicochemical attributes described above are highly dependent on the conditions under which biochar is produced. Variations in feedstock composition, pyrolysis temperature, and processing strategies can substantially modify the structural and chemical characteristics of the resulting material. Feedstock composition determines mineral content and nutrient availability [28,30] and co-pyrolysis or blending strategies can optimize surface functionality [31].

At pilot scale, locally adapted kiln systems have demonstrated the capacity to produce alkaline, carbon-rich biochar suitable for soil amendment and carbon sequestration, suggesting scalability beyond laboratory conditions [50].

In short, biochar production represents a structure–function continuum: production variables determine physicochemical properties, which in turn regulate soil reactivity, nutrient dynamics, contaminant immobilization, and long-term carbon stability.

3.2. Biochar Agronomical Applications

The growing adoption of biochar in agriculture is supported by a substantial body of evidence demonstrating its benefits. A review of several recent studies highlights multiple positive effects resulting from the application of biochar in agricultural systems, encompassing physical, chemical and biological improvements to soil, as well as increases in crop productivity and improvement of sustainability [51–53].

3.2.1. Physiochemical Soil Effects

Across field, greenhouse, and controlled incubation studies, biochar application consistently alters soil physicochemical functioning through changes in pH regulation, carbon stabilization within aggregates, cation exchange capacity, moisture–aeration dynamics, and (in some systems) nutrient availability and loss pathways. However, the magnitude and direction of these effects remain strongly dependent on biochar type, dose, soil baseline status, and experimental time scale.

(a) Soil Carbon Dynamics and Stabilization

An observed physicochemical outcome is the enhancement of soil carbon storage and its redistribution among physically protected pools. In a field study evaluating aggregate-associated carbon fractions, biochar significantly increased soil organic carbon (SOC), particularly within macroaggregates, while promoting mineral-associated organic carbon (MAOC) formation and shifting carbon functional group distribution, changes consistent with improved aggregate stability and strengthened carbon protection mechanisms [54]. This aligns with the concept that biochar can contribute not only to total SOC gains but also to more persistent carbon forms through aggregation-mediated physical protection and organo-mineral association.

In a three-year experiment in a high-latitude field evaluating diversified cover-crop systems in barley, a low annual biochar application of 1 Mg ha^{-1}/year (totalling 3 Mg ha^{-1}) was included as a treatment to assess its potential contribution to soil organic carbon (SOC) dynamics [55]. However, the biochar-fertilizer treatment showed no significant improvement in SOC stocks, nor in the particulate organic matter (POM) or mineral-associated organic matter (MAOM) pools, when compared with the fertilized monocrop barley system, even with the presence of cover crops. Importantly, although biochar did not enhance SOC stabilization within the three-year period, it did not negatively affect soil quality or crop yield, indicating that low-dose biochar applications remain agronomically safe, even if insufficient to drive measurable carbon sequestration in the short term [55].

Long-term field evidence shows that biochar can contribute substantially to soil carbon stabilization, though its effectiveness depends strongly on soil texture and biochar quality. In loamy soils, the application of carbon-rich, wood-derived biochar (31.5 Mg ha^{-1}) leads to persistent increases in soil organic carbon (SOC) for at least seven years, supported by the long-term stability of black carbon and the accumulation of highly condensed aromatic structures [56]. In contrast, high biochar additions (40 Mg ha^{-1}) on sandy soils exhibit significant SOC and black carbon losses due to limited physical protection, enhanced microbial degradation, higher susceptibility to oxidation and pronounced vertical transport of biochar particles to deeper layers. These findings indicate that biochar enhances SOC sequestration most effectively in fine-textured soils and when produced from carbon-rich feedstocks with high aromaticity [56].

Biochar significantly increased SOC in saline–alkaline soil cultivated with *Arundo donax*, with effects rising proportionally to application rate; the highest dose (30 t ha^{-1}) boosted SOC by up to 47% during the growing season. These SOC gains were driven primarily by a strong increase in microbial necromass carbon (MNC), a highly stable carbon pool, which biochar enhanced by 23–31%, thereby improving long-term SOC stabilization [57]. Collectively, these studies indicate that long-term SOC stabilization is governed by the interaction between biochar stability, soil texture and application rate. Carbon-rich, highly aromatic biochars applied to fine-textured soils consistently promoted greater carbon persistence, whereas low application rates or coarse-textured soils limited aggregate protection and long-term carbon sequestration.

(b) Soil pH and CEC

Biochar increases soil pH and enhances exchange properties, but the agronomic significance may differ between short- and longer-term responses. In a field trial testing carbon functional groups across organic fertilizer types, corn-straw biochar—characterized by phenolic and carbonyl C—raised soil pH (~+9%) and organic carbon (~+45.8%) yet produced limited short-term yield stimulation relative to more labile organic amendments [58]. This reinforces an important mechanistic distinction: biochar can shift the soil chemical environment (pH and OC) without necessarily translating into immediate productivity gains when nutrient release is constrained or when yield is not primarily pH-limited.

In semi-arid greenhouse conditions, biochar substantially increased soil CEC (reported up to +165% at 10% *v*/*v*) alongside improved microbial abundance and enzymatic activity, indicating that exchange capacity gains may be particularly consequential in low-buffering soils where nutrient retention is limiting [59]. Similarly, integrated field management approaches combining biochar and biofertilizers improved soil pH, CEC, and organic carbon, while biofertilizers primarily strengthened biological activity; the combined treatment enhanced nutrient availability and soil functioning and improved stability-based sustainability indicators [60].

Modified biochar further demonstrates how targeted physicochemical engineering can amplify soil benefits. In pathogen-challenged tomato systems, silicon-modified biochar increased soil pH, CEC, EC, and moisture, while also enhancing multiple carbon fractions (e.g., microbial biomass C and mineral-associated pools) and overall soil multifunctionality, showing that amendments can simultaneously restructure chemical buffering and carbon dynamics under biotic stress [61]. In acidic paddy soils, silica-enriched rice husk biochar improved pH, SOC, CEC, total N, and silicon availability, while concurrently reducing CH_4 emissions, indicating that biochar physicochemical effects can intersect with redox-driven processes in flooded systems [62].

(c) Soil Moisture and Physical Structure

Biochar-mediated physicochemical effects may manifest through the coupling of water and gas transport, with downstream consequences for soil oxygen status and plant senescence. Under mulched drip irrigation, biochar particle size altered the soil water–oxygen balance; optimized size fractions delayed leaf senescence and supported yield improvement, consistent with a physicochemical regulation of aeration and moisture availability in intensively managed systems [41]. This highlights that biochar action is not restricted to a matter of chemistry, but also of pore architecture and hydraulic function, which can be sensitive to particle size distribution.

Biochar may also influence soil carbon mineralization by shifting respiration partitioning and microbial processing. In a maize cropland field trial, biochar reduced heterotrophic respiration, whereas nitrogen fertilization increased autotrophic respiration; the combined treatments altered carbon flux dynamics, suggesting that biochar can moderate mineralization pathways and potentially reduce SOC losses under certain management regimes [63]. Controlled incubation data support the idea of context dependence: hemp-derived biochar modified C and N mineralization patterns and microbial carbon use efficiency (CUE) in a soil-dependent manner, with short-term stimulation of microbial activity varying across soil types [64].

Moisture regime further conditions these responses. In an Alfisol microcosm, moisture variability increased SOC decomposition and microbial biomass indicators, whereas biochar alone did not significantly change average SOC decomposition; importantly, biochar mitigated moisture-driven effects by stabilizing aggregate fractions, indicating a physicochemical buffering role under fluctuating hydrological stress [65]. This evidence points out that biochar may not universally suppress decomposition rates, but it can stabilize soil structure and dampen destabilizing environmental variability.

Notably, physicochemical changes are not guaranteed, especially under low application rates and in fertile, well-structured soils. In a 10-year no-till corn–soybean Mollisol study, a single low-rate biochar application (2.40 Mg ha^{-1}) produced no statistically significant improvements across key soil physical, chemical, or biological properties, despite some non-significant positive trends and isolated effects of cover crops [66]. This long-term evidence is important to highlight as it suggests that, under certain baseline conditions and management regimes, biochar may deliver limited measurable change at agronomically realistic low rates.

Overall, the studies reviewed indicate that physicochemical soil responses are not controlled by individual biochar properties in isolation but emerge from the interaction between biochar characteristics, intrinsic soil conditions, management practices and experimental time scale. Feedstock composition and pyrolysis conditions determine the structural and chemical attributes of biochar, whereas soil texture, mineralogy and baseline fertility regulate the extent to which these properties translate into measurable improvements in carbon stabilization, nutrient retention, water dynamics and aggregate development. Consequently, variability among studies should not be interpreted as contradictory evidence, but rather as the expression of different combinations of interacting physicochemical drivers operating under distinct agroecosystem conditions. Figure 3 below highlights the above-mentioned interactions between biochar and soil physicochemical properties.

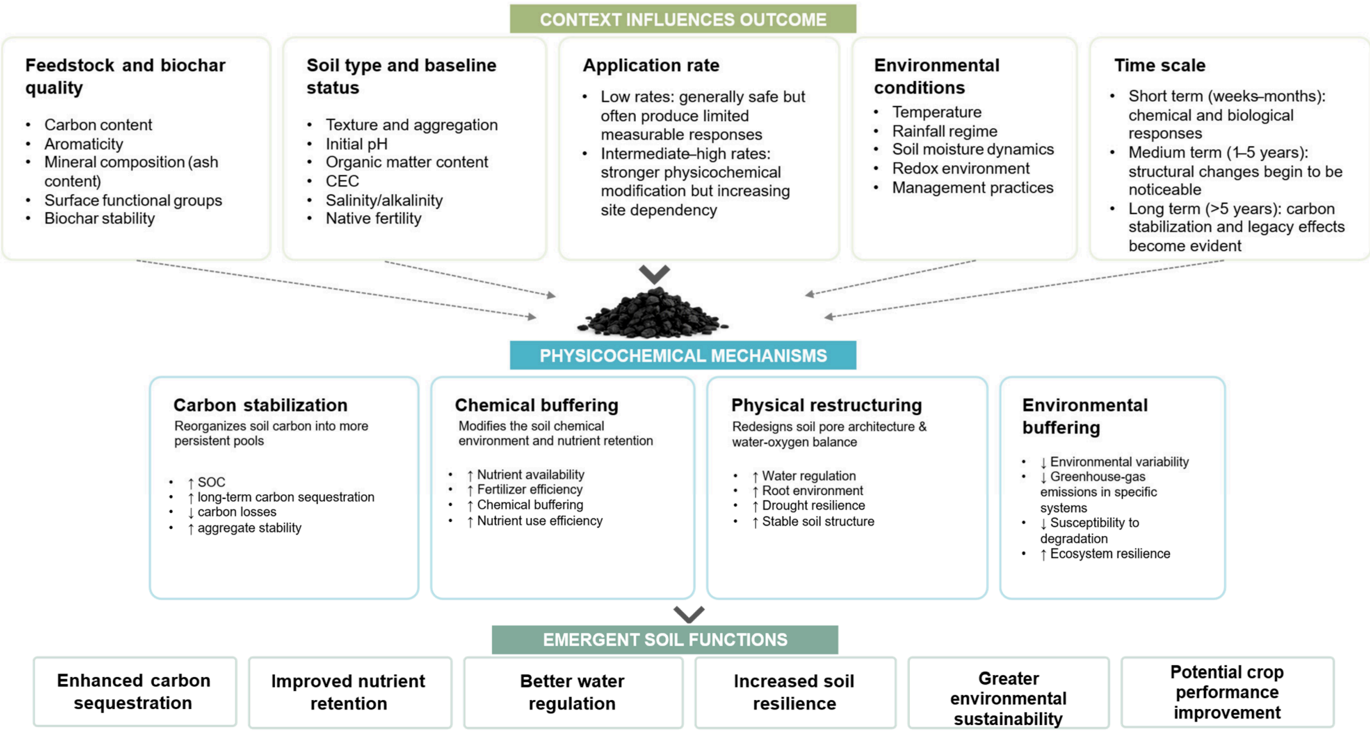

Figure 3. Conceptual framework illustrating the main physicochemical mechanisms by which biochar influences soil functioning. Biochar-induced changes in carbon dynamics, soil chemistry and physical structure interact to improve nutrient retention, aggregate stability, water–air balance and long-term soil resilience. The magnitude of these responses depends on biochar properties (feedstock, pyrolysis conditions, particle size and application rate) and site-specific soil characteristics, emphasizing the context-dependent nature of biochar performance. The arrows turning up represent improvement in corresponding factor, while the arrows turning down represent a drop in corresponding factor. Icons/illustrations included in the diagram were generated by ChatGPT (Model 5.5), a generative AI tool.

3.2.2. Biological Effects

Biochar influences soil functioning not only through physicochemical shifts, but also by reshaping microbial communities, modulating enzyme activities, and altering plant–microbe interactions in the rhizosphere. The evidence in this review indicates that biological responses are often amplified when biochar is combined with biological inputs (e.g., AMF, biofertilizers, phosphate-solubilizing bacteria), or when biochar properties are engineered (e.g., silicon-modified biochar; temperature-tailored biochar). Nevertheless, long-term field data also show that biological benefits may be minimal under low application rates in fertile, well-structured soils.

(a) Microbial Biomass and Enzyme Activity

Studies showed evidence of increased microbial activity and enzyme-mediated nutrient cycling following biochar amendments, particularly in the rhizosphere. Biochar was reported to preferentially enhance rhizosphere microbial activity relative to bulk soil, suggesting a "rhizosphere amplification" effect likely driven by biochar-induced changes in microhabitats and resource availability near roots [67]. In semi-arid greenhouse conditions, biochar at 10% (v/v) increased microbial abundance and enzymatic activity alongside improved root traits, whereas higher application (20%) showed a plateau or decline, pointing to a dose-sensitive response and potential biological trade-offs at excessive rates [59].

Field evidence from Mediterranean tomato systems indicates that biochar can improve soil chemical conditions, while biofertilizers more directly stimulate microbial biomass and enzymatic activity; notably, combined biochar + biofertilizer treatments improved overall soil biological functioning and sustainability-related indicators, even when yield responses were moderate [60]. This supports that biochar may act as a supporting matrix that enhances the effectiveness of biological inoculants by improving habitat structure and nutrient retention, rather than functioning as a stand-alone biological stimulant.

(b) Biochar as Microbial Carrier

A particularly consistent theme is biochar's role as a habitat and protective carrier for beneficial microorganisms. In degraded soils, biochar enhanced phosphate-solubilizing bacteria (PSB) survival and activity, increasing P availability and improving soil biochemical properties, evidence that biochar can facilitate microbial establishment and persistence under stressful soil conditions [68]. Similarly, biochar combined with arbuscular mycorrhizal fungi (AMF) increased maize biomass and nutrient uptake, enhanced AMF colonization, shifted bacterial and fungal community composition, and raised soil enzyme activity [69]. Together, these findings suggest that biochar can function as a biological scaffold capable of supporting symbiotic and functional microbial groups. However, the identity of the microbial taxa favoured, and the magnitude of these responses vary considerably with soil properties, biochar characteristics and inoculated microorganisms.

At a more mechanistic level, biochar can shape AMF community assembly. Using root-exclusion biochar packets, Neuberger et al. [70] showed that non-activated pinewood biochar was selectively colonized by the fungi *Paraglomerales* spp. and hosted lower AMF richness and diversity than bulk soil. AMF composition varied with soil type and nutrient amendments, and NP fertilization reduced *Paraglomerales* relative abundance [70]. This indicates that biochar does not simply "increase fungi"; rather, it filters microbial communities, favouring certain taxa depending on substrate conditions and nutrient regimes.

(c) Disease Suppression and Microbiome Dynamics

Biochar-mediated disease suppression emerges as a strong biological pathway when soils are challenged by pathogens. In a pathogen-inoculated tomato system, silicon-modified biochar (MSC) reduced *Ralstonia solanacearum*, a Gram-negative bacterium, in soil and plant tissues and sharply reduced disease index, while simultaneously enriching beneficial taxa (notably *Bacillus*) and increasing microbial network modularity, which is an ecological signature often associated with enhanced resilience and functional redundancy [61]. This is complemented by evidence that biochar production conditions matter: biochar produced at higher pyrolysis temperatures improved disease suppression, altered microbial community composition, increased beneficial taxa (including *Bacillus* spp.), reduced *R. solanacearum* abundance, and induced temperature-dependent shifts in microbial network complexity [71]. Collectively, these studies indicate that engineered biochar can promote microbial community restructuring towards disease-suppressive consortia under pathogen-challenged conditions. Nevertheless, the specific taxa involved, the stability of these microbial networks and the resulting degree of disease suppression appear to vary among cropping systems, biochar formulations and environmental conditions.

(d) Plant-Microbe Interactions

Biochar can also influence microbial processes tied to nitrogen cycling and greenhouse gas formation, particularly denitrification. In a long-term wheat system on saline–alkali soils, biochar rate and application frequency reshaped microbial communities and metabolic profiles, reduced cumulative N_2O emissions, decreased denitrifying taxa, increased nitrogen-fixing groups, and enhanced plant N uptake, suggesting microbial restructuring consistent with suppressed denitrification and improved nitrogen retention [72]. Although this study is often discussed under climate mitigation, its central mechanism is microbial: biochar appears to shift soil microbial functional balance in ways that reduce N losses and support nutrient capture.

Beyond community composition and enzyme activity, biochar can influence the biochemical dialogue between roots and microbes. In wheat, biochar reshaped rhizosphere bacterial diversity and altered root metabolite profiles (including amino acids, organic acids, and secondary metabolites), strengthening coordinated metabolomic–microbial associations related to nutrient cycling and plant growth [73]. This provides a more integrated view: biochar's biological effects can be mediated through root exudation patterns and microbial selection, creating feedback loops that influence nutrient availability and plant performance.

Long-term evidence cautions against assuming universal biological improvements. In a 10-year no-till corn–soybean Mollisol study, a single low-rate biochar application (2.40 Mg ha^{-1}) produced no statistically significant changes in microbial biomass groups or other biological indicators, despite some non-significant positive trends; cover crops increased soil K only [66]. This piece of evidence suggests that in fertile systems and at low rates, biochar may be biologically inert at the scale detectable by standard indicators, or its effects may require longer time frames, different rates, or stronger soil constraints to emerge. Below, in Table 5, the key biological effects and mechanisms of biochar on soil and plants have been summarized.

Table 5. Summary of the main biological effects of biochar on soil ecosystems and plant–microbe interactions.

Biological Process	Main Observed Effects	Main Mechanisms	Key Observations	Source
Microbial biomass and enzyme activity	Increased microbial biomass, enzyme activity and nutrient cycling, particularly in the rhizosphere	Improved microhabitats, greater nutrient retention and enhanced root development	Responses are dose-dependent; moderate applications stimulate biological activity, whereas excessive rates may lead to a plateau or decline. Biochar alone often acts as a supporting matrix rather than a direct biological stimulant.	[57,58,65]
Biochar as a microbial carrier	Improved survival, colonization and activity of beneficial microorganisms (PSB, AMF); enhanced nutrient acquisition	High porosity and large surface area provide protected habitats and facilitate microbial establishment	Biochar functions as a biological scaffold, particularly in degraded soils. Microbial responses depend on soil type and nutrient regime.	[66–68]

Table 5. *Cont.*

Biological Process	Main Observed Effects	Main Mechanisms	Key Observations	Source
Disease suppression and microbiome dynamics	Reduced pathogen abundance and disease severity; enrichment of beneficial taxa (e.g., *Bacillus* spp.); increased microbial network stability	Restructuring of microbial communities and promotion of disease-suppressive microbiomes	Biochar properties strongly influence suppressive capacity. Silicon-modified biochar and high-temperature biochar showed superior performance against *Ralstonia solanacearum*.	[59,69]
Plant–microbe interactions	Improved nitrogen uptake, reduced denitrification, lower N_2O emissions, altered rhizosphere microbial diversity and root metabolite profiles	Microbial community restructuring, enhanced root exudation and coordinated metabolomic–microbial interactions	Biochar influences plant performance indirectly through regulation of microbial functional groups and rhizosphere biochemical communication.	[70,71]
Long-term biological responses	Limited or no measurable changes in microbial biomass and biological indicators under some field conditions	Low application rates and initially fertile, well-structured soils reduce detectable responses	Long-term benefits are not universal and depend on soil constraints, application rate and experimental duration.	[64]

3.2.3. Soil Hydraulics Effect

Water regulation is one of the most frequently cited agronomic benefits of biochar application. However, recent field-based evidence indicates that biochar effects on soil hydrology are not uniformly positive and may vary according to depth, season, slope, and climatic regime.

(a) Water Retention

Biochar application has been consistently associated with improvements in soil hydraulic properties, primarily through its influence on soil structure, porosity, and water retention capacity. Its high carbon content, large specific surface area, and porous architecture enhance the soil's ability to store and retain water, thereby increasing plant-available water, particularly in coarse-textured soils [74,75]. Experimental evidence shows that biochar amendments can significantly increase water retention, with reported gains ranging from approximately 48% to 129% depending on application rate, highlighting a clear dose-dependent response [75].

Meta-analytical studies further confirm that biochar improves water retention capacity (WRC), with average increases proportional to application rate and more pronounced effects in sandy soils, where baseline water-holding capacity is low [74,76]. These improvements are largely driven by modifications in pore size distribution, including the formation of additional micropores and capillary pores that enhance water storage, while simultaneously reducing bulk density and improving soil aggregation. However, responses vary across soil textures, with limited or even negative effects on plant-available water reported in clay-rich soils due to increased water retention at higher tensions [77].

However, in a karst sloping system monitored under natural rainfall, biochar application (30 and 60 t ha^{-1}) altered vertical moisture distribution rather than increasing total soil water storage [78]. Continuous time domain reflectometry (TDR) monitoring showed that biochar reduced moisture in the surface layer (0–10 cm) while increasing it in subsurface layers (10–30 cm), suggesting a redistribution effect. Moreover, biochar delayed soil moisture response to rainfall events and reduced infiltration rates relative to the control. Importantly, total soil water storage (SWS) was not significantly increased ($p > 0.05$) [78].

These findings indicate that in sloping, bare-soil systems, biochar may modify hydraulic conductivity and temporal response to rainfall without necessarily enhancing overall water storage capacity.

While biochar generally enhances soil water retention through structural improvements and increased porosity, the reported studies showed that its effects on soil hydrodynamics remain context-dependent, with outcomes varying according to soil texture, application rate, and landscape conditions, and in some cases leading to water redistribution rather than net gains in total water storage.

(b) Erosion Control

Beyond water retention, biochar also alters soil hydrodynamics by enhancing infiltration and reducing runoff and erosion. Reported increases in infiltration can reach up to 80%, while runoff and erosion reductions may exceed 90% in certain systems, reflecting improved pore connectivity and structural stability [79]. Long-term field evidence supports these findings, demonstrating substantial increases in soil water storage, improved moisture retention during drought periods, and enhanced soil "sponge function" under natural rainfall conditions [80].

In addition, long-term evidence from an 11-year soybean system on sloping farmland demonstrated that biochar improved soil hydrological properties and reduced erosion indicators [81]. Beyond water retention improvements, biochar alleviated barriers associated with continuous cropping and enhanced soybean yield stability. The erosion-reduction effect is particularly relevant in sloped systems, where runoff control and soil conservation are tightly linked to water management.

Overall, the evidence indicates that biochar not only enhances soil water retention but also improves hydrological functioning by strengthening infiltration, reducing runoff and erosion, and promoting long-term soil water storage, thereby contributing to greater system resilience and yield stability, particularly in erosion-prone and water-limited environments. Importantly, biochar effects are not static but evolve over time. Ageing processes in soil can increase surface hydrophilicity and enhance water absorption, although interactions with fertilization practices may alter pore accessibility and reduce water uptake capacity [82]. Additionally, biochar performance depends on production conditions, with lower-temperature biochar and those derived from more labile feedstocks often exhibiting greater effectiveness in improving soil water dynamics [76].

Further nuance is provided by field experiments in subtropical red soils (Ultisols), where biochar effects differed between wet and dry periods [83]. In this study, biochar increased soil water storage during wet seasons but intensified soil drying during prolonged drought. This indicates that moisture retention benefits are season-dependent and may depend on antecedent soil moisture conditions and evaporative demand.

Such studies imply that biochar can enhance water capture during rainfall-abundant periods but may also accelerate depletion under extended dry spells, potentially due to modified pore connectivity or altered capillary flow dynamics. Consequently, hydrological outcomes appear strongly context-dependent, influenced by climate regime, soil type, and rainfall distribution patterns. The illustration below, Figure 4, outlines how biochar reorganizes the soil pore network and influences both soil water retention and erosion.

3.2.4. Crop Quality and Productivity

Across the studies synthesized here, biochar effects on crop performance are best understood as context-dependent and frequently management-mediated. Yield gains and improvements in nitrogen use efficiency (NUE) tend to be strongest when biochar is integrated with optimized nutrient regimes, microbial amendments, or stress-mitigation strategies, whereas biochar alone may deliver limited short-term yield responses in already fertile systems or when nutrient constraints are not addressed.

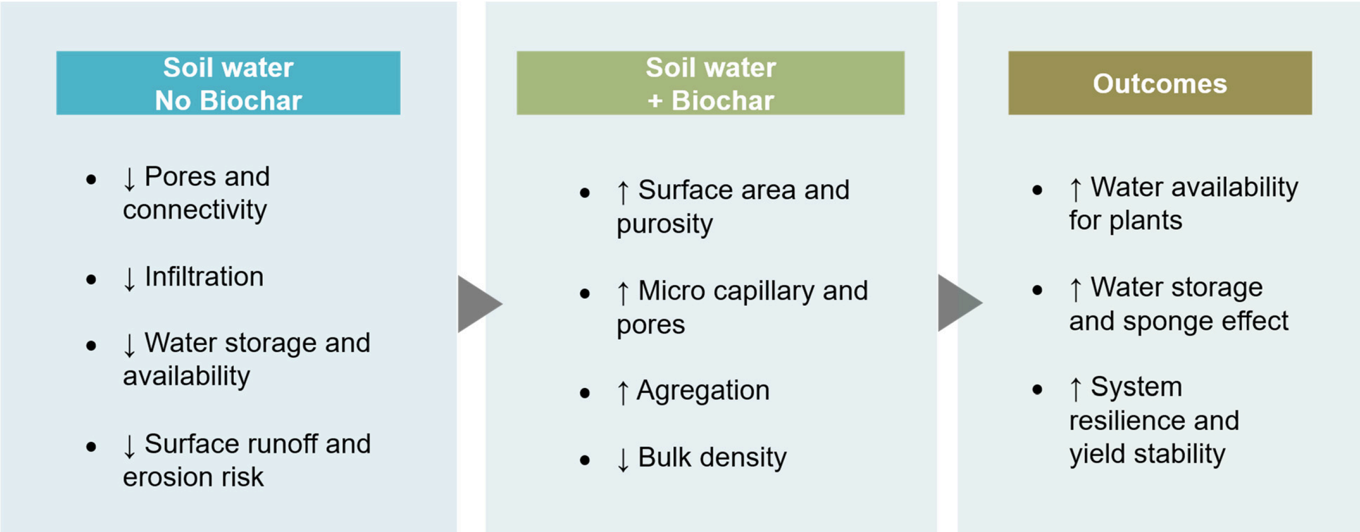

Figure 4. Biochar-mediated regulation of soil hydraulic functioning. Biochar regulates the complete soil water cycle by modifying pore architecture, water storage, infiltration and runoff pathways. Rather than uniformly increasing soil moisture, biochar redistributes and controls water movement within the soil profile. Consequently, hydraulic benefits emerge from improved regulation of water capture, storage and transport, while their magnitude remains strongly dependent on soil texture, climate, landscape position, biochar properties and time. The turning up arrows represent an improvement in factors while the turning down arrows represent a drop in factors.

(a) Yield and Nutrient Use Efficiency

Studies indicate that biochar can enhance crop productivity when paired with appropriately calibrated fertilizer inputs. In winter wheat, biochar combined with an optimum nitrogen rate increased grain yield while also improving lodging resistance and nitrogen agronomic efficiency, indicating that biochar can contribute to both productivity and standability via improved plant mechanical traits and N capture [84]. Similarly, a field maize study in Ethiopia reported that biochar combined with optimal inorganic fertilizer rates increased yield and yield components compared with sole fertilizer or control treatments [85].

Beyond conventional fertilization, "biochar-as-fertilizer-platform" approaches show concrete promise. Multi-season field trials demonstrated that biochar-based fertilizer formulations maintained yields while reducing nutrient inputs, improving NUE, and delivering superior cost-effectiveness relative to standard fertilization [86]. Complementary evidence from controlled systems shows that biochar-based controlled-release fertilizers can synchronize nutrient availability with plant demand: BC–ammonium phosphate improved wheat biomass and grain yield while reducing nutrient leaching and stabilizing soil available N and P over time [87]. Likewise, nanobiochar coatings on Diammonium Phosphate (DAP) slowed nutrient release and, at optimized coating levels, improved maize dry matter yield and markedly increased N, P, and K uptake; however, excessive coating strength constrained nutrient availability in the short-duration crop window, illustrating an important design trade-off [88]. Together, these studies suggest that biochar reliably improves NUE when it functions as a nutrient-retention and nutrient-delivery interface, rather than as a generic soil amendment.

In addition, a global meta-analysis restricted to field studies across major cereals found that biochar (especially when combined with fertilizers) increased yields (with the largest gains in wheat), enhanced SOC and C: N ratio, and reduced greenhouse gas intensity metrics, implying that productivity benefits can co-occur with improved nutrient and carbon efficiency under real agronomic conditions [89].

Under sub-optimal nutrient supply, biochar can enhance crop growth indirectly by strengthening plant physiological performance. In leafy vegetables grown under nutrient stress, compost + biochar significantly improved photosynthetic efficiency, antioxidant enzyme responses, and biomass compared with single amendments, indicating synergy between labile organic inputs and biochar's retention/habitat functions [90]. This evidence hints that biochar may provide a stabilizing physicochemical environment, while compost supplies readily mineralizable nutrients, synergistically improving plant function under constrained nutrition.

(b) Feedstock Effects on Yield Response

Not all biochar-associated chemical improvements translate into immediate yield gains. In maize, biochar rich in phenolic and carbonyl functional groups increased soil pH and organic carbon but showed limited short-term yield stimulation, whereas more labile carbon fractions in other organic amendments were more strongly associated with vegetative growth and yield-linked nutrient availability [58]. This suggests that biochar chemistry (including the balance of labile vs. condensed carbon functional groups) can determine whether early yield benefits emerge, particularly in short-duration trials.

Feedstock effects were also evident in water spinach, where plant-waste-derived biochar improved soil chemical status and increased biomass and chlorophyll, while also enhancing antioxidant compounds and influencing sensory attributes; however, responses differed by feedstock type, reinforcing that "biochar" is not a single agronomic input but a family of materials with variable plant outcomes [91].

Evidence from a recent field-based meta-analysis further reinforces the importance of feedstock selection for agronomic performance. Biochars produced from animal wastes consistently generated larger yield responses than those derived from crop residues, whereas woody biochars generally showed limited effects on crop productivity. These differences were attributed to the higher nutrient availability of animal-derived biochars, while woody biochars, despite their greater carbon stability, typically exhibit higher C:N ratios and lower fertilizing capacity. Importantly, the meta-analysis also emphasized that feedstock effects interact with pyrolysis temperature, soil properties and climate, indicating that crop responses arise from the combined influence of biochar production and deployment conditions rather than from feedstock type alone [92].

(c) Stress Mitigation in Crops

Several studies show that biochar can ameliorate crop performance under abiotic stress, often through improved ion homeostasis, reduced oxidative damage, and enhanced nutrient capture.

In coastal saline soils, a biochar–plant growth-promoting bacteria composite improved rice biomass and chlorophyll, strengthened antioxidant activity, improved Na^+/K^+ balance, and reduced salt stress indicators relative to single amendments [93]. For wheat seedlings exposed to combined salinity and drought, biochar combined with GA_3 improved germination, biomass, relative water content, and photosynthetic pigments compared to stressed controls and single-factor treatments, indicating additive or synergistic stress buffering [94]. Under heavy metal co-contamination (Sb + Pb), biochar + GABA increased rice grain yield while reducing oxidative stress and lowering metal accumulation, highlighting the potential for biochar-based strategies to protect yield under toxic constraints [95].

Biochar can also improve food safety while sustaining productivity in contaminated soils. In wheat grown under Pb stress, biochar combined with montmorillonite reduced DTPA-extractable Pb, sharply reduced Pb in grain, improved biomass and chlorophyll, reduced oxidative stress markers, and lowered health risk indices, illustrating that yield and risk mitigation can be jointly optimized through composite amendments [96]. Comparable effects were reported for rapeseed using Fe-modified biochar, which reduced bioavailable Cd and Cr, improved antioxidant responses, and increased seed yield alongside oil and protein quality improvements [97]. Earlier evidence in PTE-contaminated acidic soils also showed that peanut shell biochar improved *Brassica* spp. biomass and pigment status while lowering metal bioavailability and plant uptake, consistent with improved growth through stress alleviation [98].

Salinity-related yield gains can be particularly striking when biochar is engineered at finer scales. Rice-straw-derived biochar nanoparticles dramatically increased tomato fruit yield under salt stress and improved Na translocation more strongly than regular biochar, indicating that particle scale and reactivity can alter the magnitude of stress mitigation [99]. In pot systems, moss-derived biochar combined with TiO_2 nanoparticles improved growth and pigment traits under salinity while reducing stress enzyme indicators, suggesting multi-input strategies can support plant performance under osmotic and ionic stress [100].

(d) Crop Structures Development and Quality

Biochar can stimulate root development and aboveground biomass, supporting yield formation and sometimes quality traits. In *Agave* spp., 10% biochar increased leaf area and biomass and improved root traits, alongside higher CEC and microbial/enzymatic activity; however, higher biochar concentration reduced marginal gains, reinforcing the importance of dose optimization [59]. In soilless cherry tomato production, biochar incorporation increased leaf area, root length and surface area, biomass, flower number, and fruit number, while also enhancing fruit antioxidant-related quality (e.g., lycopene), indicating that biochar can influence both yield determinants and quality attributes in controlled substrates [101]. Field broccoli data likewise showed that enriched biochar and manure-based treatments increased yield and modified mineral composition and phytochemical profiles, although synergy was not always additive across amendment combinations [102]. In contrast, a 10-year no-till corn–soybean Mollisol experiment found no statistically significant improvements in soil properties or biological indicators at a low biochar rate (2.40 Mg ha^{-1}), and correspondingly no strong evidence of agronomic gains under those conditions [66]. Similarly, in a two-year field trial on fresh-market tomato, biochar had no significant effect on growth or yield, although it reduced a fruit disorder (zippering) and improved profitability when paired with poultry litter, suggesting that benefits may emerge through quality and economics rather than yield per se [103]. In alkaline Mediterranean Luvisol conditions, multiple amendments (including wood biochar) produced limited effects on barley biomass overall, with compost and some ash mixtures showing stronger growth responses than biochar alone [104]. These cases importantly underscore that biochar is not universally yield-enhancing, and its effectiveness depends on baseline soil limitations, crop sensitivity, amendment dose, and the presence of complementary nutrient or biological drivers.

Table 6 presents the key takeaways from biochar's influence on crop yield and quality.

Overall, the above-mentioned studies hint that, rather than seeking a universally superior biochar, future agronomic strategies should prioritize feedstock selection according to the desired soil or crop function, recognizing that different biomass sources produce biochars optimized for distinct agronomic objectives.

Table 6. Summary of the main effects of biochar on crop quality and productivity under different agronomic conditions.

Agronomic Response	Main Observed Effects	Main Influencing Factors	Key Observations	Source
Yield and nitrogen use efficiency (NUE)	Increased grain yield, improved NUE, greater lodging resistance and enhanced nutrient uptake	Fertilizer optimization, nutrient availability, biochar–fertilizer interactions	Yield improvements are generally strongest when biochar is combined with optimized fertilization or nutrient-retention strategies rather than applied alone. Biochar-based fertilizers and controlled-release formulations further enhance nutrient synchronization and fertilizer-use efficiency.	[82–87]
Abiotic stress mitigation	Improved tolerance to salinity, drought and heavy-metal stress; increased photosynthesis, antioxidant activity, nutrient uptake and grain yield	Biochar engineering, microbial inoculants, nanoparticles, plant growth regulators	Biochar performs particularly well under stressful conditions, where improvements are mainly associated with enhanced physiological resilience, ion homeostasis and reduced oxidative damage.	[90–97]
Crop development and quality	Increased root growth, leaf area, biomass, flower and fruit production; improved antioxidant compounds, oil/protein quality and reduced fruit disorders	Application rate, cultivation system, complementary amendments	Biochar can improve both yield components and crop quality, although responses are frequently enhanced by organic amendments or optimized management practices.	[57,98–100]

3.2.5. Agronomic Sustainability

Beyond short-term yield responses, biochar contributes to agronomic sustainability through its effects on contaminant immobilization, greenhouse gas (GHG) mitigation, nutrient cycling regulation, and long-term system resilience. The literature synthesized here indicates that biochar can contribute to agronomic sustainability through multiple mechanisms. However, the strength and persistence of these benefits remain variable across studies and depend on feedstock properties, application rate, soil type, management practices and the duration of field observations.

(a) Trace Metal Immobilization

A sustainability function of biochar is the reduction in trace metal bioavailability in contaminated or peri-urban agricultural soils. In a greenhouse study with *Lactuca sativa*, Turull et al. [105] showed that biochar (particularly at 6%) significantly reduced Cr and Pb uptake, while compost more strongly reduced exchangeable metal fractions. Importantly, diffuse gradients in thin-film (DGT) measurements correlated well with plant uptake, whereas total soil metal concentrations were poorly predictive. This confirms that biochar primarily alters bioavailable pools rather than total metal stocks, highlighting the importance of speciation-based assessments in sustainability evaluations.

Under controlled heavy metal stress, biochar-based strategies also improved crop safety and performance. Biochar combined with montmorillonite significantly reduced extractable Pb and grain Pb concentration in wheat while improving biomass and reducing oxidative stress [96]. Similarly, Fe-modified biochar reduced exchangeable Cd and Cr fractions and markedly increased rapeseed yield while enhancing oil and protein quality [97]. In acidic, PTE-contaminated soils, peanut shell biochar reduced bioavailable Cr, Ni, As, Cd, and Pb and improved *Brassica* spp. biomass and physiological performance [98]. Collectively, these findings demonstrate that biochar can simultaneously enhance productivity and reduce contaminant transfer to edible tissues, contributing directly to food safety.

(b) Greenhouse Gas and Climate Mitigation

Biochar also contributes to sustainability by modifying soil carbon dynamics and GHG emissions. A global meta-analysis of field studies across maize, wheat, and rice systems reported significant reductions in N_2O emissions, decreased CH_4 emissions in paddy systems, reduced global warming potential and greenhouse gas intensity, and increases in soil organic carbon [89]. Emission reductions were most pronounced when biochar was combined with fertilizers, suggesting synergy between nutrient management and biochar-mediated regulation of soil microbial processes.

In paddy systems, silica-enriched biochar reduced CH_4 emissions while improving soil chemical properties and rice performance [62]. Complementary evidence indicates that biochar can restructure microbial communities and suppress denitrification pathways, reducing N_2O emissions while enhancing nitrogen retention and plant uptake [72]. These studies position biochar as both a carbon stabilization strategy and a regulator of soil biogeochemical fluxes. However, CO_2 responses remain variable across systems [89], underscoring the importance of system-specific assessment. Although reductions in N_2O and CH_4 emissions are among the most consistently reported environmental benefits, the magnitude of these effects varies considerably among cropping systems and experimental conditions, highlighting the need for additional long-term field validation.

(c) Long-term Soil Resilience

Sustainability also encompasses long-term soil functionality and yield stability. In an 11-year sloping soybean system, biochar improved hydrological properties, reduced erosion indicators, and enhanced yield stability under continuous cropping [81]. Such cumulative improvements suggest structural and ecological effects that may strengthen resilience over time.

Conversely, in fertile Mollisols under low biochar application rates, long-term improvements in soil properties and biological indicators were not statistically significant [66]. This contrast may highlight that biochar benefits are more evident where baseline soil constraints exist (e.g., contamination, erosion risk, nutrient inefficiency), whereas responses may be limited in already well-functioning systems.

Figure 5 outlines the several ways in which biochar is able to improve agronomic sustainability.

All in all, current evidence supports biochar as a promising component of sustainable agricultural management, but long-term agronomic sustainability should be viewed as an emerging rather than fully established outcome. Future multi-site, multi-year field experiments will be essential to determine the consistency, persistence and scalability of these benefits under diverse agricultural conditions.

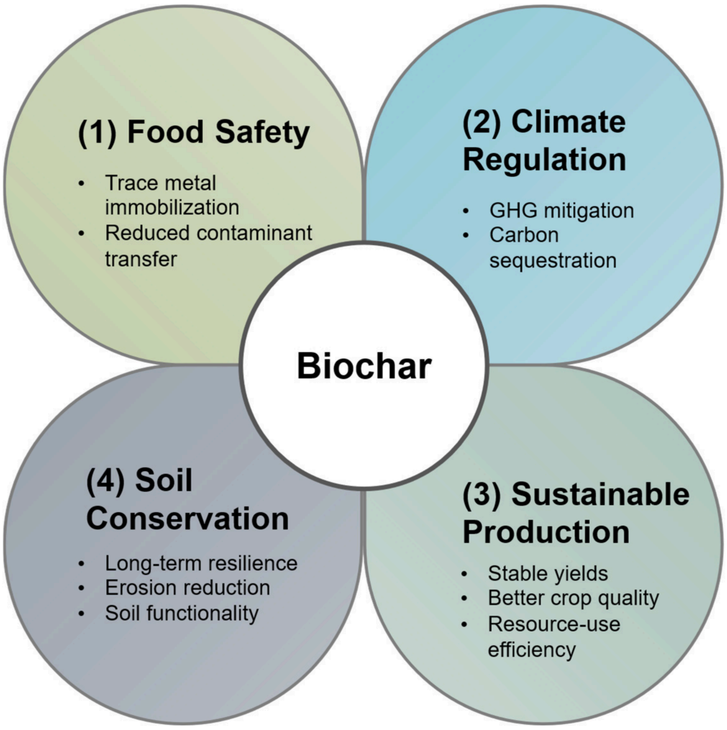

Figure 5. Diagram of biochar as an ecosystem service provider. By delivering multiple ecosystem services simultaneously, biochar strengthens soil functionality, reduces environmental risks, improves productivity and builds resilient agroecosystems over time.

3.3. Limitations and Uncertainties

While the evidence shows that biochar can enhance crop performance and nutrient use efficiency, particularly when integrated with optimized fertilization, engineered nutrient-delivery systems, and stress-mitigation strategies, the outcomes remain highly variable across soils, climates, and management contexts [84,86,89]. This variability highlights an essential point for sustainable deployment: biochar is not a universally yield-enhancing input, but a material whose benefits depend on matching its properties and application regime to site-specific constraints [58,66,103]. Therefore, the next section touches on the main limitations and trade-offs related to biochar performance, including dose–response uncertainty, inconsistent long-term effects in fertile soils, interaction effects with nutrient inputs and soil biology, economic feasibility, and potential environmental risks.

3.3.1. Biochar Response Variability

One of the greatest challenges currently limiting the widespread implementation of biochar in agriculture is the remarkable variability of agronomic responses reported across the scientific literature. Such variability, however, should not necessarily be interpreted as contradictory evidence. Rather, it reflects the inherently multifactorial nature of biochar–soil–plant interactions, where multiple physical, chemical, biological, and environmental processes operate simultaneously. Understanding the sources of this variability has therefore become one of the principal scientific challenges for advancing biochar research from proof-of-concept studies towards reliable and context-specific/personalized agronomic applications.

Intrinsic variability among biochars constitutes one of the primary sources of heterogeneity in agronomic responses. Although biochars are often discussed as a single class of soil amendments, variations in feedstock type, pyrolysis temperature, residence time, and post-processing conditions can produce biochars with markedly different pH, surface area, nutrient content and adsorption capacity, often resulting in inconsistent agronomic responses across studies and environments [8]. Freitas et al. [106], for example, demonstrated that plant- and animal-derived biochars differed by more than two orders of magnitude in plant-available phosphorus, with poultry litter biochar containing 13,100–16,900 mg kg^{-1} of Mehlich-3 extractable P compared with only 67–480 mg kg^{-1} in wood-derived biochars. Importantly, even two poultry litter biochars produced by the same manufacturer but from different production batches exhibited distinct nutrient compositions and phosphorus release patterns, indicating that feedstock alone does not guarantee consistent agronomic behaviour. Furthermore, the study showed that total nutrient concentration was not necessarily indicative of nutrient availability; despite containing the highest total phosphorus content, biosolids-derived biochar released substantially less plant-available phosphorus because much of the phosphorus was associated with relatively stable mineral phases containing Fe, Al and Mg. These findings illustrate that the agronomic performance of biochar depends not only on the quantity of nutrients present but also on their chemical speciation and bioavailability. Consequently, biochars with apparently similar origins may produce markedly different crop responses [106].

Another example is the characterization of biochar produced in a mobile artisanal kiln from açaí residues, which revealed substantial variability in physicochemical properties, including ash content, fixed carbon, pH and mineral composition across production batches. Such variability reflects the difficulty of controlling temperature and oxygen availability in low-technology pyrolysis systems, highlighting the challenges of ensuring consistent biochar quality for agricultural applications [107]. Besides that, in a review focused on biochar water absorption, Lund et al. [108] reported highly divergent effects across 18 studies, with water retention responses ranging from modest increases to improvements as high as 628%. Importantly, contrasting pyrolysis temperatures produced beneficial effects through different mechanisms, with low-temperature biochars favouring hydrophilicity and high-temperature biochars enhancing porosity and surface area [108]. This illustrates that variability in biochar performance does not necessarily reflect contradictory evidence, but rather the operation of different mechanisms under different material and soil conditions.

The agronomic performance of biochar is also highly dependent on soil characteristics and cropping systems. Positive responses are generally more pronounced in degraded, acidic or nutrient-poor soils, whereas fertile soils often show limited yield responses [8].

Finally, the temporal dimension of biochar performance further contributes to the heterogeneity of agronomic responses reported in the literature. In a global data synthesis comprising 38 long-term field experiments and 161 paired comparisons, Zhang et al. [109] demonstrated that biochar increased crop yield by an average of 14%, but this overall value masked important temporal dynamics. Yield gains were 12% during the first five years following application, increasing to 21% in experiments lasting more than five years. Interestingly, while biochar enhanced crop productivity, it also increased yield variability by 27% in short-term experiments, whereas no significant effect on yield variability was observed in long-term trials [109]. These findings suggest that the mechanisms governing biochar performance evolve over time. Initially, crop responses are largely driven by liming effects and the release of readily available nutrients, both of which tend to decline after the first few years. Conversely, long-term improvements appear to result from the gradual enhancement of soil structure, nutrient retention, water-holding capacity, and resilience to climatic stress, leading to more stable crop production. Consequently, studies conducted over different experimental durations may report contrasting agronomic responses without necessarily being contradictory.

3.3.2. Application Rates and Management Uncertainty

Agronomic responses to biochar are often non-linear and strongly dependent on application rate. High doses may induce nutrient imbalances, temporary nitrogen immobilization, excessive pH increases and reductions in microbial diversity, ultimately compromising crop performance [110,111].

Yield responses were also influenced by management practices, particularly biochar application rates and fertilization regimes. Higher yield gains were associated with biochar additions above 20 Mg ha^{-1} and under crop rotation systems, indicating that biochar effectiveness is closely linked to agronomic management strategies [109].

Application rates reported in the literature vary widely, ranging from a few tonnes per hectare in field trials to several tens of tonnes per hectare in experimental conditions. Such variability reflects the absence of standardized agronomic guidelines and contributes to uncertainty in practical management recommendations [8].

In addition to application rates, the method of biochar incorporation can strongly influence agronomic outcomes. Field experiments comparing broadcast, spot and ring applications demonstrated that localized placement near the root zone significantly enhanced plant growth, yield, and nutrient uptake compared with uniform soil incorporation. These results highlight that biochar management practices remain insufficiently standardized and can substantially influence the effectiveness of biochar amendments [112].

Another important challenge concerns the accurate quantification of biochar-derived carbon in soils. Experimental assessments indicate that conventional soil sampling approaches may not adequately capture the spatial variability of biochar distribution after field application, potentially leading to substantial uncertainty in carbon accounting. This limitation is particularly relevant in the context of climate mitigation policies and carbon credit schemes, where reliable estimates of long-term carbon sequestration are required [113].

3.3.3. Standardization

Part of the apparent inconsistency reported across the biochar literature may also arise from methodological limitations rather than from contradictory biochar behaviour itself. In a systematic review of 26 global meta-analyses, Schmidt et al. [114] identified incomplete biochar characterization as one of the major sources of uncertainty affecting the interpretation of agronomic responses. The authors argue that insufficient reporting of key physicochemical properties hampers comparisons among studies, as biochars with markedly different characteristics are frequently treated as equivalent amendments. Furthermore, they highlight additional methodological limitations, including inconsistent data harmonization, limited assessment of publication bias, and insufficient consideration of non-independent observations, all of which may contribute to the high heterogeneity commonly observed across meta-analyses [114]. These findings emphasize that improving both biochar characterization and experimental reporting is essential for generating more reliable and transferable agronomic recommendations. Recognizing these limitations, recent efforts have increasingly shifted from highlighting the need for standardization towards the development of internationally recognized certification schemes and quality standards for biochar.

Addressing the inherent variability of biochar requires not only more rigorous experimental methodologies but also internationally harmonized quality standards capable of ensuring product consistency, safety and traceability. Köves et al. [115] argue that standardization should extend beyond laboratory characterization to encompass the entire biochar value chain, integrating sustainable production practices, sustainable application strategies, quality assurance, and regulatory oversight. In this context, internationally recognized certification schemes, including the International Biochar Initiative (IBI), the European Biochar

Certificate (EBC), and the British Biochar Quality Mandate (BQM), establish standardized criteria for feedstock selection, production processes, physicochemical characterization, contaminant thresholds, and product traceability. Beyond defining minimum quality requirements, these frameworks increasingly incorporate sustainability metrics such as life cycle assessment, greenhouse gas emissions, energy efficiency, feedstock sourcing, and environmental labelling, reflecting a broader transition from product certification towards sustainability certification. Nevertheless, despite these important advances, regulatory harmonization remains incomplete. The absence of universally accepted standards and the continuous emergence of new production technologies indicate that biochar standardization should be regarded as an adaptive process requiring regular revision as scientific knowledge evolves [115].

Standardization should not aim to produce a single definition of an "ideal" biochar. Instead, future certification systems should recognize the diversity of biochars while ensuring that each material is consistently characterized, transparently documented, and appropriately matched to its intended agronomic application. Consequently, harmonization should focus on the standardization of characterization protocols and reporting practices rather than on imposing uniformity on inherently heterogeneous materials.

Beyond improving methodological consistency in research, several international initiatives have sought to establish standardized frameworks for biochar quality assessment and certification. According to Divyangkumar and Panwar [116], organizations such as the International Biochar Initiative (IBI), the European Biochar Certificate (EBC), and the Biochar Quality Mandate (BQM) have developed guidelines defining minimum quality criteria for biochar intended for agricultural use. These certification schemes specify acceptable feedstocks, production requirements, physicochemical properties (e.g., organic carbon content, H/C and O/C molar ratios, pH, electrical conductivity and particle size distribution) and maximum thresholds for contaminants such as heavy metals and polycyclic aromatic hydrocarbons. Furthermore, several countries have already incorporated biochar into national regulations governing fertilizers and soil amendments, reflecting the growing recognition that standardized quality control is essential for ensuring product safety, reproducibility and wider adoption [116]. Nevertheless, the authors also acknowledge that the diversity of feedstocks, production technologies and intended applications continues to challenge the development of universally applicable standards, highlighting the need for further harmonization of certification criteria across regulatory frameworks.

3.3.4. Economic and Technical Constraints

Production costs remain one of the principal obstacles to commercial deployment. Recent techno-economic analyses demonstrate that the cost of biochar is highly dependent on the production technology employed. John et al. [117] reported that small-scale experimental production systems can generate prohibitively high production costs, whereas larger and better-optimized pyrolysis units substantially improve economic performance. Nevertheless, labour requirements continue to represent a major proportion of total production costs, particularly in decentralized production systems where biomass collection, kiln operation and process monitoring remain largely manual. Importantly, the authors emphasize that increased crop productivity alone does not necessarily guarantee economic viability, since profitability depends on the interaction between production costs, crop value, application rates, persistence of benefits and local market conditions. They further suggest that phased biochar application, technological optimization and the integration of carbon credit mechanisms may partially improve financial feasibility, although these approaches remain highly context-dependent [117].

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Beyond production economics, the commercial success of biochar is strongly influenced by the efficiency of the entire supply chain. As highlighted by Zilberman et al. [118], biochar should not be evaluated as an isolated product but rather as one component of an integrated pyrolysis system capable of simultaneously generating biochar, bio-oil, syngas and other value-added products. Such integrated biorefinery approaches may substantially improve the overall economic performance by diversifying revenue streams and maximizing biomass valorization. Feedstock availability and logistics also play a central role in determining production costs, with transportation representing a significant challenge due to the low bulk density and high moisture content of many agricultural residues. Consequently, decentralized production systems, modular pyrolysis units and the utilization of locally available biomass resources have been proposed as promising strategies to reduce logistical costs and improve economic efficiency [118].

Despite continuous technological advances, the transition of biochar from promising research material to broadly adopted agricultural technology requires considerably more than improvements in production efficiency alone. Zilberman et al. [118] argue that large-scale commercialization will depend on coordinated technological, logistical and institutional developments, including standardized quality certification, supportive public policies, effective extension services, demonstration programmes and mechanisms capable of remunerating ecosystem services such as carbon sequestration. Therefore, overcoming the current economic and technical barriers requires integrated value-chain development together with policy support that facilitates investment, market development and long-term adoption of biochar technologies.

Low-technology pyrolysis systems may improve accessibility of biochar production in rural contexts, particularly where agricultural residues are abundant. The use of mobile handmade kilns has been proposed as a practical approach for decentralized biochar production from agro-industrial residues such as açaí waste. However, these systems often operate with limited control over temperature and oxygen conditions, resulting in variability in biochar quality and potentially lower process efficiency [107].

Economic feasibility remains one of the main barriers to large-scale biochar deployment. Cost–benefit analyses indicate that biochar production based solely on the commercialization of the product may remain economically unviable due to high capital and operational costs. In contrast, profitability substantially improves when biochar systems are integrated into carbon markets such as voluntary carbon trading schemes or emissions trading systems [119].

The economic feasibility of biochar systems is strongly influenced by policy frameworks and carbon market mechanisms. Cost–benefit analyses indicate that biochar production may remain economically unviable when relying solely on product sales, whereas profitability significantly improves when carbon credits are included through voluntary markets or emissions trading schemes. However, this dependence introduces policy uncertainty, as the future integration of biochar carbon removals into regulatory systems such as the EU ETS remains under discussion [119].

Furthermore, economic feasibility is closely intertwined with environmental uncertainty, since the long-term persistence of biochar in soil and the durability of its agronomic benefits remain key determinants of return on investment. These aspects are discussed in the following section.

3.3.5. Long-Term Environmental Uncertainties

Environmental risks associated with feedstock type and the release of contaminants such as heavy metals or toxic organic compounds are identified as potential adverse effects when biomass sources are not rigorously controlled [20,21,120].

Several recent reviews have emphasized that biochar may generate unintended environmental effects depending on feedstock composition, pyrolysis conditions, contaminant load, particle size, ageing dynamics and site-specific soil–water interactions. Xiang et al. [121] showed that potential risks may occur across multiple environmental compartments, including soil, water and atmosphere, through mechanisms such as the release of heavy metals and toxic organic compounds, atmospheric dispersion of fine particles, pollutant mobilization in aquatic systems and ecotoxicological effects associated with micro- and nanobiochar.

Within the soil environment, these risks are particularly complex because properties commonly regarded as beneficial may become adverse under specific conditions. Brtnicky et al. [122] noted that biochar can negatively affect water availability, nutrient dynamics, pH balance, agrochemical efficacy and microbial communities, especially when inappropriate feedstocks, excessive application rates or poorly matched soil conditions are involved. For example, excessive alkalinization may reduce micronutrient availability, nutrient adsorption may limit plant uptake, and some biochars may introduce or mobilize contaminants rather than immobilize them [122]. This highlights that biochar effects should not be evaluated only through average positive responses, but also through the probability of neutral or negative outcomes under specific edaphic and management contexts.

More recently, Dong et al. [123] advanced this discussion by distinguishing between endogenous risks, originating from the biochar itself, and exogenous risks, acquired after environmental application. Endogenous risks include heavy metals, PAHs, volatile organic compounds and environmentally persistent free radicals, whereas exogenous risks may arise from ageing, contaminant adsorption–desorption processes, fragmentation into nano-sized particles and secondary pollutant release. This distinction is particularly useful because it shows that biochar is not environmentally static after soil incorporation. Its surface chemistry, porosity, functional groups and contaminant-binding capacity evolve over time, meaning that a material initially acting as a contaminant sink may later become a secondary source under changing environmental conditions [123].

Taken together, these studies indicate that environmental uncertainty in biochar application arises from the interaction between intrinsic material properties, environmental transformation processes and site-specific exposure pathways. Therefore, future assessments should move beyond simple classifications of biochar as either beneficial or harmful and adopt risk-based frameworks incorporating feedstock screening, contaminant speciation, ecotoxicological testing, particle-size assessment, long-term monitoring and life cycle assessment. Such an approach would allow biochar deployment to remain aligned with climate-smart and regenerative agriculture goals while minimizing unintended environmental impacts.

The literature also highlights uncertainty regarding the long-term impacts of biochar on ecosystems, given the predominance of short-term and laboratory-based studies [19,124]. Also, many positive effects emerge only after several cropping cycles, while initial negative impacts may occur if biochar is not properly integrated into soil management and fertilization strategies [111,125].

Biochar amendments may also interact with native soil organic matter, potentially stimulating its mineralization through priming effects. Such interactions may offset part of the carbon sequestration benefits expected from biochar additions, introducing uncertainty in long-term climate mitigation estimates [126].

Biochar may also influence temporal yield stability. A synthesis of long-term field experiments showed that while biochar increased mean crop yields by approximately 14%, it also increased yield variability in the short term due to the transient nature of its liming and fertilization effects. Over longer periods, however, yield variability tended to stabilize as soil properties gradually improved [109].

In addition, field experiments using isotopically labelled biochar have demonstrated measurable mineralization rates, indicating that biochar carbon is not completely inert and may gradually decompose over time. The longevity of biochar is influenced not only by its intrinsic properties, such as aromatic condensation and elemental composition, but also by environmental conditions including soil mineralogy, microbial activity, and climate. Furthermore, biochar ageing involves a dynamic balance between degradation processes (such as microbial oxidation, physical fragmentation and leaching) and stabilization mechanisms, including aggregation with soil particles and interactions with mineral phases [127]. Predicting the long-term fate of biochar therefore remains challenging, particularly given that most available field experiments cover only a few decades, while the processes governing carbon persistence operate on centennial timescales.

Field evidence also indicates that biochar persistence may be lower than often assumed. In a 15-month field study conducted in Florida, losses of pyrogenic carbon ranged from 17.5% to 93.3% per year depending on feedstock and pyrolysis conditions, even for biochar produced at high temperatures. The study also observed interactions between biochar and native soil organic carbon, suggesting potential priming effects that may accelerate carbon turnover under certain environmental conditions [126].

3.4. Towards Optimized Biochar Deployment

The rapid expansion of biochar research over the past two decades has substantially improved our understanding of its physicochemical properties and agronomic potential. Current evidence indicates that the central challenge is no longer to demonstrate whether biochar can benefit agricultural systems, but rather to determine how it can be optimally produced, characterized and deployed under specific environmental and socioeconomic conditions. The increasing recognition of response variability, methodological inconsistencies, economic limitations and environmental uncertainties suggests that future research should progressively shift from demonstrating isolated benefits towards developing integrated deployment strategies capable of maximizing agronomic performance while ensuring environmental safety, economic feasibility and long-term sustainability.

3.4.1. Moving from Generalized Applications to Tailored Biochars

One of the most promising research directions involves the development of customized biochars designed for specific soil constraints, climatic conditions and cropping systems. Rather than considering biochar as a universal soil amendment, future studies should prioritize the optimization of feedstock selection, pyrolysis conditions, particle size and post-production modifications according to clearly defined agronomic objectives. Such an approach would allow biochar properties to be tailored to the requirements of individual production systems, thereby reducing the variability that currently characterizes field responses.

3.4.2. Standardization as a Prerequisite for Reproducibility

Future progress will also depend on the adoption of harmonized protocols for biochar production, characterization and experimental reporting. International certification schemes such as the International Biochar Initiative (IBI) and the European Biochar Certificate (EBC) already provide important foundations for quality assurance. However, broader harmonization of physicochemical characterization, contaminant assessment, reporting standards and field methodologies remains necessary to improve reproducibility and facilitate meaningful comparisons among studies. Standardization should therefore focus not on producing a single "ideal" biochar, but on ensuring that every biochar is

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consistently characterized, transparently documented and appropriately matched to its intended application.

3.4.3. Long-Term, Multi-Site Field Validation

Despite the growing number of field studies, long-term evidence remains comparatively limited. Future experiments should extend beyond short-term productivity assessments to evaluate the persistence of biochar effects under contrasting climatic conditions, soil types and management practices. Multi-site experiments integrating agronomic performance, soil health indicators, greenhouse gas emissions, carbon persistence, nutrient cycling and microbial dynamics will be essential to establish robust recommendations for large-scale agricultural implementation.

3.4.4. Integrating Environmental and Economic Assessments

Future research should increasingly combine agronomic evaluations with Life Cycle Assessment (LCA), Techno-Economic Assessment (TEA), environmental risk assessment and spatial biomass availability analyses. Such integrated approaches would provide a more realistic assessment of biochar sustainability by simultaneously considering carbon sequestration, production costs, logistical constraints, environmental trade-offs and ecosystem services. This systems-based perspective would allow decision-makers to identify locally optimized deployment strategies rather than relying on generalized recommendations.

3.4.5. From Research to Implementation

Ultimately, the successful transition of biochar from experimental research to mainstream agricultural practice will require coordinated advances that extend well beyond technological innovation. Wider adoption will depend on the development of robust certification systems, adaptive regulatory frameworks, carbon market integration, farmer training, extension services and evidence-based public policies capable of supporting context-specific implementation. Consequently, biochar should no longer be viewed merely as a soil amendment, but rather as a component of integrated agricultural systems that simultaneously contribute to sustainable biomass management, circular bioeconomy, climate change mitigation and resilient food production.

The future of biochar research lies not in solely and repeatedly demonstrating its potential benefits, but in understanding the conditions under which those benefits can be consistently achieved. As the field matures, research priorities should progressively evolve from proving biochar effectiveness towards optimizing its production, characterization, deployment and long-term monitoring within integrated agricultural systems. Such a transition represents a necessary step for transforming biochar from a promising experimental technology into a scientifically robust, economically viable and environmentally responsible solution for sustainable agriculture.

Another important aspect is improving the robustness and transparency of evidence synthesis. Given the growing body of biochar literature, future systematic reviews and meta-analyses should explicitly address potential publication bias towards positive outcomes by incorporating neutral and negative field results, applying standardized quality assessment criteria, and adopting harmonized reporting protocols. Such approaches will provide a more balanced and reliable evidence base to support science-based recommendations and large-scale implementation.

Figure 6 presents a suggestion of a framework or iterative cycle to optimize biochar use in an agricultural context.

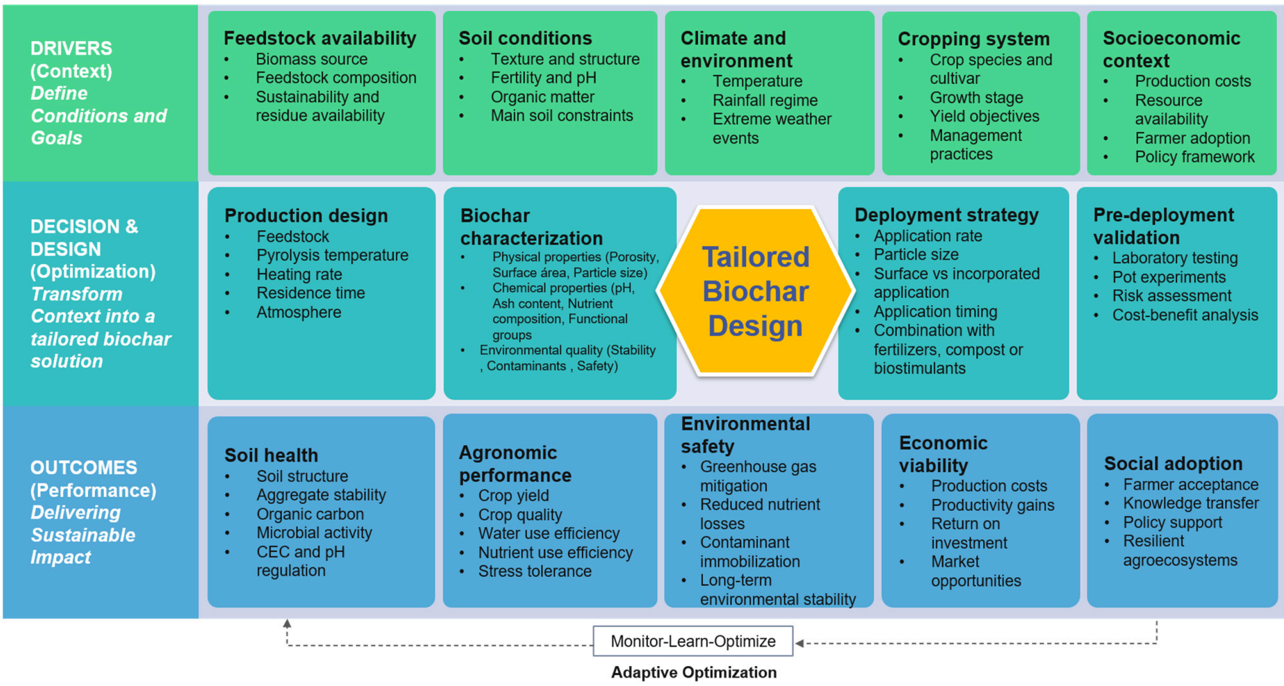

Figure 6. Integrated Biochar Deployment Framework (IBDF) illustrating a context-driven strategy for optimizing biochar implementation in agricultural systems.

This framework conceptualizes biochar deployment as a multistage decision process rather than a generic amendment strategy. Contextual drivers (feedstock availability, soil conditions, climate, cropping system and socioeconomic constraints) define application objectives and guide biochar production, characterization, deployment strategy and pre-deployment validation toward the design of tailored biochars. Successful implementation is evaluated through multiple performance dimensions, encompassing agronomic performance, soil health improvement, environmental safety, economic viability and social adoption. Continuous monitoring and evidence generation establish a feedback loop that supports adaptive optimization and long-term sustainable biochar deployment.

4. Conclusions

The evidence synthesized throughout this review suggests that biochar performance emerges from a sequence of interconnected processes rather than from any single intrinsic property. Feedstock selection and pyrolysis conditions determine the physicochemical characteristics of biochar, which subsequently regulate its interactions with soil physical, chemical and biological processes. These interactions ultimately influence nutrient cycling, carbon stabilization, water regulation, crop productivity and broader sustainability outcomes. Consequently, the variability reported across studies should not be interpreted as contradictory evidence, but rather as the result of different combinations of biochar properties, soil characteristics, environmental conditions and management practices operating within distinct agroecosystems.

Four key points should be taken away from this review:

1. Feedstock selection and pyrolysis conditions are the primary determinants of biochar functionality, governing its physicochemical properties and subsequent interactions with soil and crops.
2. The agronomic performance of biochar is fundamentally system-dependent, emerging from the interaction between biochar properties, soil characteristics and management practices rather than from any single factor.

3. The most consistent benefits are observed in degraded or resource-limited systems, where improvements in nutrient retention, water regulation, carbon stabilization and stress mitigation translate more readily into agronomic gains.
4. Current research priorities should shift from demonstrating biochar effectiveness towards optimizing its production, characterization and deployment, supported by standardized methodologies and long-term field validation.

The future of biochar research therefore lies less in repeatedly demonstrating whether biochar works, and more in understanding how different biochars can be designed, characterized and deployed to consistently deliver specific agronomic functions under diverse agricultural conditions.

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References

1. Hultgren, A.; Carleton, T.; Delgado, M.; Gergel, D.R.; Greenstone, M.; Houser, T.; Hsiang, S.; Jina, A.; Kopp, R.E.; Malevich, S.B.; et al. Impacts of Climate Change on Global Agriculture Accounting for Adaptation. *Nature* **2025**, *642*, 644–652. [CrossRef] [PubMed]
2. Auer, C.; Reyer, C.P.O.; Adamczak, W.; Aylett, C.; Benzie, M.; Berndt, J.P.; Bresch, D.N.; Bosello, F.; Bressan, G.; Carter, T.R.; et al. Critical Intervention Points for European Adaptation to Cascading Climate Change Impacts. *Nat. Clim. Chang.* **2025**, *15*, 1226–1233. [CrossRef]
3. de Souza, N.R.D.; Solberg, M.K.M.; Hu, X.; Cherubini, F. Environmental Benefits and Changes in Ecosystem Services of Climate-Smart Agriculture Relative to Conventional Agriculture in Norway. *J. Environ. Manag.* **2025**, *377*, 124633. [CrossRef] [PubMed]
4. Kohl, L.; Minarsch, E.-M.L.; Niether, W.; Dix, B.A.; Kammann, C.; Clifton-Brown, J.C.; Gattinger, A. Early Evidence for the Benefits of Biochar in Organic Regenerative Agriculture. *Sci. Rep.* **2026**, *16*, 7833. [CrossRef] [PubMed]
5. Ng, S.; Hinrichsen, O.; Viswanathan, S. Contextual Conditions Define Maximum Energy-Use Threshold in Low-Carbon Controlled Environment Agriculture for Agri-Food Transformation. *Nat. Commun.* **2026**, *17*, 880. [CrossRef] [PubMed]
6. Jones, D.L.; Cooledge, E.C.; Alston, D.; Chadwick, D.R. Agricultural Management Strategies to Actively Promote Subsoil Carbon Storage. *Soil Tillage Res.* **2026**, *256*, 106846. [CrossRef]
7. Zhang, X.; Geng, X.; Zhu, J.; Wang, L.; Ma, W.; Liu, Y.; Sheng, X.; Qi, X.; Chen, Y.; Gao, P.; et al. Sustainable Agronomic and Tillage Strategies for Rice–Wheat Rotation Systems in Saline–Alkali Soils: Lessons, Advances, and Prospects. *Field Crops Res.* **2026**, *337*, 110278. [CrossRef]
8. Junejo, A.R.; Liu, J.; Chen, K.; Dahri, S.H.; Junejo, Y.; Li, H. Biochar for Sustainable and Climate-Resilient Agriculture: The 3Ps Approach. *Biomass Bioenergy* **2026**, *210*, 109001. [CrossRef]

9. Waheed, A.; Xu, H.; Qiao, X.; Aili, A.; Yiremaikebayi, Y.; Haitao, D.; Muhammad, M. Biochar in Sustainable Agriculture and Climate Mitigation: Mechanisms, Challenges, and Applications in the Circular Bioeconomy. *Biomass Bioenergy* **2025**, *193*, 107531. [CrossRef]
10. Wei, Q.; Wei, Q.; Xu, J.; Chen, P.; Li, Z.; Qi, Z. Biochar for Agricultural Soil Carbon Sequestration and CO_2 Mitigation: A Bibliometric Analysis of Research Hotspots, Gaps and Climate-Resilient Pathways. *Appl. Soil Ecol.* **2026**, *218*, 106672. [CrossRef]
11. Frank, S.; Augustynczik, A.L.D.; Havlík, P.; Boere, E.; Ermolieva, T.; Fricko, O.; Di Fulvio, F.; Gusti, M.; Krisztin, T.; Lauri, P.; et al. Enhanced Agricultural Carbon Sinks Provide Benefits for Farmers and the Climate. *Nat. Food* **2024**, *5*, 742–753. [CrossRef] [PubMed]
12. Weng, Z.H.; Cowie, A.L. Estimates Vary but Credible Evidence Points to Gigaton-Scale Climate Change Mitigation Potential of Biochar. *Commun. Earth Environ.* **2025**, *6*, 259. [CrossRef]
13. Ogunwa, K.I.; Nnadozie, E.C.; Dube, N.; Oladoye, P.O.; Obayomi, K.S. The Evolving Role of Biochar: Recent Advances and Future Directions—A Review. *Biomass Bioenergy* **2026**, *208*, 108844. [CrossRef]
14. Zubairu, A.M.; Marjanović, J.; Abdulkadir, M.; Eldawwy, N.; Takács, A.; Ocansey, C.M.; Gulyás, M. Conceptual Framework for Restoring Soil Fertility in Arid Borno State, Nigeria with Biochar from Agricultural Wastes. *Discov. Sustain.* **2025**, *7*, 7. [CrossRef]
15. Awogbemi, O.; Kallon, D.V.V.; Ray, R.C. Recent Advancements in Biochar Functionalization from Crop Residues for a Green Future. *J. Renew. Mater.* **2025**, *13*, 2191–2233. [CrossRef]
16. Bo, X.; Zhang, Z.; Wang, J.; Guo, S.; Li, Z.; Lin, H.; Huang, Y.; Han, Z.; Kuzyakov, Y.; Zou, J. Benefits and Limitations of Biochar for Climate-Smart Agriculture: A Review and Case Study from China. *Biochar* **2023**, *5*, 77. [CrossRef]
17. Siddiqui, S. Unlocking the Environmental Potential of Biochar: Production, Applications, and Limitations. *Front. Sustain. Food Syst.* **2025**, *9*, 1569941. [CrossRef]
18. Upadhyay, V.; Choudhary, K.K.; Agrawal, S.B. Use of Biochar as a Sustainable Agronomic Tool, Its Limitations and Impact on Environment: A Review. *Discov. Agric.* **2024**, *2*, 20. [CrossRef]
19. Chen, W.; Meng, J.; Han, X.; Lan, Y.; Zhang, W. Past, Present, and Future of Biochar. *Biochar* **2019**, *1*, 75–87. [CrossRef]
20. Kumar, A.; Bhattacharya, T. Biochar: A Sustainable Solution. *Environ. Dev. Sustain.* **2021**, *23*, 6642–6680. [CrossRef]
21. Ayaz, M.; Feizienė, D.; Tilvikienė, V.; Akhtar, K.; Stulpinaitė, U.; Iqbal, R. Biochar Role in the Sustainability of Agriculture and Environment. *Sustainability* **2021**, *13*, 1330. [CrossRef]
22. Mukherjee, A.; Patra, B.R.; Podder, J.; Dalai, A.K. Synthesis of Biochar From Lignocellulosic Biomass for Diverse Industrial Applications and Energy Harvesting: Effects of Pyrolysis Conditions on the Physicochemical Properties of Biochar. *Front. Mater.* **2022**, *9*, 870184. [CrossRef]
23. Pandey, D.; Daverey, A.; Arunachalam, K. Biochar: Production, Properties and Emerging Role as a Support for Enzyme Immobilization. *J. Clean. Prod.* **2020**, *255*, 120267. [CrossRef]
24. Varkolu, M.; Gundekari, S.; Omvesh; Palla, V.C.S.; Kumar, P.; Bhattacharjee, S.; Vinodkumar, T. Recent Advances in Biochar Production, Characterization, and Environmental Applications. *Catalysts* **2025**, *15*, 243. [CrossRef]
25. Sakhiya, A.K.; Anand, A.; Kaushal, P. Production, Activation, and Applications of Biochar in Recent Times. *Biochar* **2020**, *2*, 253–285. [CrossRef]
26. Kalus, K.; Koziel, J.; Opaliński, S. A Review of Biochar Properties and Their Utilization in Crop Agriculture and Livestock Production. *Appl. Sci.* **2019**, *9*, 3494. [CrossRef]
27. Rani, M.; Abideen, Z.; Munir, N.; Hasnain, M.; Mehdizadeh, M.; Qasim, M.; Radicetti, E. Enhancing Soil Fertility, Nutrient Recovery and Carbon Sequestration: The Role of Biochar, Composted Biochar, and Biochar-Compost Mixtures in Sustainable Agriculture. *J. Trace Elem. Miner.* **2026**, *15*, 100276. [CrossRef]
28. Busari, B.I.; Ezzat, A.O.; Emmanuel, S.S.; Yusuf, R.O.; Iwuozor, K.O.; Emenike, E.C.; Emeghai, J.; Al-Lohedan, H.A.; Adeniyi, A.G. Comparative Structural and Textural Evaluation of Biochar Derived from Devolatilized Agricultural Pods. *Bioenerg. Res.* **2025**, *19*, 3. [CrossRef]
29. Adekanye, T.; Dada, O.; Kolapo, J. Pyrolysis of Maize Cob at Different Temperatures for Biochar Production: Proximate, Ultimate and Spectroscopic Characterisation. *Res. Agric. Eng.* **2022**, *68*, 27–34. [CrossRef]
30. İlay, R. Biochar Production from Various Low-Cost Marine Wastes Using Different Production Methods: Characterization of Biochar and Marine Feedstock for Agricultural Purposes. *Mar. Pollut. Bull.* **2024**, *205*, 116623. [CrossRef]
31. Basika, E.; Komakech, A.J.; Kizito, S.S.; Lee, R.D.; Schwarzböck, T. Slow Co-Pyrolysis of Faecal Sludge and Rice Husks into Biochar. *Biomass Bioenergy* **2026**, *206*, 108688. [CrossRef]
32. Wang, J.; Wang, S. Preparation, Modification and Environmental Application of Biochar: A Review. *J. Clean. Prod.* **2019**, *227*, 1002–1022. [CrossRef]
33. Xie, Y.; Wang, L.; Li, H.; Westholm, L.J.; Carvalho, L.; Thorin, E.; Yu, Z.; Yu, X.; Skreiberg, Ø. A Critical Review on Production, Modification and Utilization of Biochar. *J. Anal. Appl. Pyrolysis* **2022**, *161*, 105405. [CrossRef]
34. Do, P.T.M.; Nguyen, L.X. A Review of Thermochemical Decomposition Techniques for Biochar Production. *Environ. Dev. Sustain.* **2024**. [CrossRef]

35. Gabhane, J.W.; Bhange, V.P.; Patil, P.D.; Bankar, S.T.; Kumar, S. Recent Trends in Biochar Production Methods and Its Application as a Soil Health Conditioner: A Review. *SN Appl. Sci.* **2020**, *2*, 1307. [CrossRef]
36. Da Silva, J.C.G.; Rodrigues, L.A.M.; Alcântara, J.P.D.; Alves, J.L.F.; Gabriel Filho, J.B.; Pereira, G.A.G.; Mockaitis, G. From Semi-Arid Biomass to Carbon Sequestration: Role of Pyrolysis Atmosphere and Temperature on Agave-Derived Biochar Properties. *Biomass Bioenergy* **2026**, *204*, 108430. [CrossRef]
37. Pinzon-Nuñez, D.A.; Adarme-Duran, C.A.; Vargas-Fiallo, L.; Rodriguez-Lopez, N.; Rios-Reyes, C.A. Biochar as a Waste Management Strategy for Cadmium Contaminated Cocoa Pod Husk Residues. *Int. J. Recycl. Org. Waste Agric.* **2022**, *11*, 101–115. [CrossRef]
38. Huang, W.-H.; Lee, D.-J.; Huang, C. Modification on Biochars for Applications: A Research Update. *Bioresour. Technol.* **2021**, *319*, 124100. [CrossRef] [PubMed]
39. Fakhar, A.; Galgo, S.J.C.; Canatoy, R.C.; Rafique, M.; Sarfraz, R.; Farooque, A.A.; Khan, M.I. Advancing Modified Biochar for Sustainable Agriculture: A Comprehensive Review on Characterization, Analysis, and Soil Performance. *Biochar* **2025**, *7*, 8. [CrossRef] [PubMed]
40. Ali, A.; Ahmad, W.; Munsif, F.; Khan, A.; Nepal, J.; Wójcik-Gront, E.; Ahmad, I.; Khan, M.S.; Ullah, I.; Akbar, S.; et al. Residual Effect of Finely-Ground Biochar Inoculated with Bio-Fertilization Impact on Productivity in a Lentil–Maize Cropping System. *Agronomy* **2022**, *12*, 2036. [CrossRef]
41. Zhou, L.; Tao, H.; Qiliang, Y.; Feng, H.; Siddique, K.H.M.; Jin, T. Biochar Particle Size Shapes Soil Water–Oxygen Conditions and Delays Senescence in Sweet Corn under Mulched Drip Irrigation. *Soil Tillage Res.* **2026**, *258*, 107049. [CrossRef]
42. Raczkiewicz, M.; Akachukwu, D.; Oleszczuk, P. Nanoscale Biochar Outperforms Conventional Biochar in Enhancing Soil Health and Reducing Risks from Polycyclic Aromatic Hydrocarbon-Contaminated Soil. *Environ. Res.* **2026**, *288*, 123161. [CrossRef] [PubMed]
43. Walz, I.L.; Dittmann, M.; Leifeld, J. Recovery and Composition of Biochar after Feeding to Cattle. *Biochar* **2026**, *8*, 13. [CrossRef]
44. Díaz, B.; Sommer-Márquez, A.; Ordoñez, P.E.; Bastardo-González, E.; Ricaurte, M.; Navas-Cárdenas, C. Synthesis Methods, Properties, and Modifications of Biochar-Based Materials for Wastewater Treatment: A Review. *Resources* **2024**, *13*, 8. [CrossRef]
45. Luo, P.; Zhang, W.; Xiao, D.; Hu, J.; Li, N.; Yang, J. Biochar-Based Fertilizers: Advancements, Applications, and Future Directions in Sustainable Agriculture—A Review. *Agronomy* **2025**, *15*, 1104. [CrossRef]
46. Ghassemi-Golezani, K.; Rahimzadeh, S. Biochar Modification and Application to Improve Soil Fertility and Crop Productivity. *Agriculture* **2022**, *68*, 45–61. [CrossRef]
47. Marshall, J.; Muhlack, R.; Morton, B.J.; Dunnigan, L.; Chittleborough, D.; Kwong, C.W. Pyrolysis Temperature Effects on Biochar–Water Interactions and Application for Improved Water Holding Capacity in Vineyard Soils. *Soil Syst.* **2019**, *3*, 27. [CrossRef]
48. Curcio, I.; Gigli, R.; Mormile, F.; Mormile, C. A Comprehensive Review on Biochar, with a Particular Focus on Nano Properties and Applications. *Nano Trends* **2025**, *10*, 100117. [CrossRef]
49. Zhang, H.; Cheng, Y.; Zhong, Y.; Ni, J.; Wei, R.; Chen, W. Roles of Biochars' Properties in Their Water-Holding Capacity and Bound Water Evaporation: Quantitative Importance and Controlling Mechanism. *Biochar* **2024**, *6*, 30. [CrossRef]
50. Adoko, K.F.; Kombienou, P.D.; Azontondé, H.A.; Cornelis, W. Development of a Pilot Kiln and Characterization of Biochars for Agricultural Use and Carbon Sequestration in Benin. *Biomass Bioenergy* **2026**, *206*, 108666. [CrossRef]
51. Maroušek, J.; Strunecký, O.; Stehel, V. Biochar Farming: Defining Economically Perspective Applications. *Clean. Technol. Environ. Policy* **2019**, *21*, 1389–1395. [CrossRef]
52. Dwibedi, S.K.; Pandey, V.C.; Divyasree, D.; Bajpai, O. Biochar-based Land Development. *Land Degrad. Dev.* **2022**, *33*, 1139–1158. [CrossRef]
53. Li, S.; Tasnady, D. Biochar for Soil Carbon Sequestration: Current Knowledge, Mechanisms, and Future Perspectives. *C* **2023**, *9*, 67. [CrossRef]
54. Yan, S.; Zhang, S.; Yan, P.; Wei, Z.; Niu, X.; Zhang, H. Biochar Application Increased Soil Carbon Sequestration by Altering Organic Carbon Components in Aggregates. *Soil Tillage Res.* **2026**, *255*, 106795. [CrossRef]
55. Inagaki, T.M.; Bøe, F.; Sturite, I.; Budai, A.; Aas, A.; Rasse, D. Root Development as a Driver of Mineral-Associated Organic Matter Formation in Cover Crop Systems of High-Latitude Agriculture. *Agric. Ecosyst. Environ.* **2026**, *396*, 109968. [CrossRef]
56. Gross, A.; Bromm, T.; Polifka, S.; Fischer, D.; Glaser, B. Long-Term Biochar and Soil Organic Carbon Stability—Evidence from Field Experiments in Germany. *Sci. Total Environ.* **2024**, *954*, 176340. [CrossRef]
57. Wang, Y.; Gao, Y.; Zheng, H.; Wang, R.; Ge, Z.; Miao, Z. Biochar Enhances Soil Organic Carbon by Stabilizing Microbial Necromass Carbon in Saline–Alkaline Topsoil. *Agronomy* **2025**, *15*, 2472. [CrossRef]
58. Song, X.; Li, J.; Ning, L.; Xu, C.; Du, W.; Liu, X.; Ding, W.; Hu, F. Linking Functional Groups of Organic Fertilizers to Soil Properties, Crop Productivity, and Yield: Evidence from a Field Experiment. *Soil Tillage Res.* **2026**, *256*, 106904. [CrossRef]

59. Narciso Ferreira, P.H.; Silva, N.V.; Woloche, C.S.; De Sousa, J.E.S.; Da Silva, J.C.G.; Cassiano, G.H.; Pereira, V.H.; Carazzolle, M.F.; Pereira, G.A.G.; De Abreu, L.G.F. Influence of Biochar on Agave Development and on Soil Characteristics from a Brazilian Semi-Arid Region. *Biomass Bioenergy* **2026**, *205*, 108497. [CrossRef]
60. Graziano, S.; Caldara, M.; Gullì, M.; Cornali, S.; Vassura, I.; Coralli, I.; Pagano, L.; Marmiroli, M.; Donati, M.; Bevivino, A.; et al. Improving the Sustainability of Tomato Production with Biochar and Biofertilizers in Emilia-Romagna, Italy. *Soil Use Manag.* **2025**, *41*, e70091. [CrossRef]
61. Wang, S.; Zhang, T.; Jahan, I.; Pan, B.; Cai, Y.; Cai, K. Silicon-Modified Biochar Suppresses Bacterial Wilt and Enhances Rhizosphere Soil Health via Microbiome Modulation and Carbon Sequestration. *Plant Soil* **2025**, *516*, 593–610. [CrossRef]
62. Sofyan, E.T.; Citraresmini, A.; Marganingrum, D.; Mulyono, A.; Djuwansah, R.; Bachtiar, T.; Nurjayati, R.; Rachmawati, V.; Hidawati, H.; Irwandhi, I. Assessment of Silica-Enriched Biochar for Enhancing Soil Fertility and Mitigating Methane Emissions in Acid-Stressed Rice Fields. *J. Ecol. Eng.* **2025**, *26*, 148–160. [CrossRef] [PubMed]
63. Niu, Y.; Chen, Z.; Liu, D.; Ding, W. Contrasting Effects of Biochar and N Fertilization on Soil Heterotrophic and Autotrophic Respiration in a Maize Cropland. *Soil Ecol. Lett.* **2026**, *8*, 250374. [CrossRef]
64. Yanardağ, İ.H. Short-Term Effects of Hemp-Derived Amendments on Soil C and N Turnover and Microbial Efficiency across Three Soil Types. *J. Soil Sci. Plant Nutr.* **2026**, *26*, 842–864. [CrossRef]
65. Pan, Y.; Tan, T.; Ren, R.; Meng, J.; Yu, N.; Jin, X.; Zhang, Y.; Zou, H.; Bolan, N.; Siddique, K.H.M. Soil Organic Carbon Decomposition in Response to Moisture, Microbial Communities, and Biochar Addition in Alfisols. *Biochar* **2026**, *8*, 5. [CrossRef]
66. Blanco-Canqui, H.; Jasa, P. Minimal Impacts of Low Biochar Rate and Cover Crop Mix on a Mollisol after 10 Years. *Bioenerg. Res.* **2026**, *19*, 21. [CrossRef]
67. Abdul-Aziz, A.-L.; Uz, I. Biochar from Agricultural Waste Enhances Rhizosphere Microbial Activity Over Bulk Soil. *J. Soil Sci. Plant Nutr.* **2026**, *26*, 2614–2627. [CrossRef]
68. Da França, R.F.; De Araújo, A.P.; Da Costa, D.P.; Lima, J.R.D.S.; Leite, M.C.D.B.S.; Silva, T.D.G.E.D.; Da Silva, A.S.; Duda, G.P.; Araujo, A.S.F.; Hammecker, C.; et al. Biochar as a Protective Layer Boosts Phosphate-Solubilizing Bacteria Effects on Phosphorus and Microbial Activity in Degraded Soils. *Land Degrad. Dev.* **2026**, *37*, 5294–5303. [CrossRef]
69. Dong, W.; Qin, J.; Chun, J.; Yang, X.; Ou, L.; Zhou, T.; Liu, F.; Xu, Y. Synergistic Effects of Biochar and Arbuscular Mycorrhizal Fungi on Maize Growth: Insights into Nutrient Uptake and Microbial Community Shifts. *Ind. Crops Prod.* **2026**, *239*, 122467. [CrossRef]
70. Neuberger, P.; Romero, C.; Kim, K.; Hao, X.; McAllister, T.A.; Ngo, S.; Li, C.; Gorzelak, M.A. Biochar Is Colonized by Select Arbuscular Mycorrhizal Fungi in Agricultural Soils. *Mycorrhiza* **2024**, *34*, 191–201. [CrossRef] [PubMed]
71. Li, S.; Yang, L.; Jiang, T.; Ahmed, W.; Mei, F.; Zhang, J.; Zhang, T.; Yang, Y.; Peng, X.; Shan, Q.; et al. Unraveling the Role of Pyrolysis Temperature in Biochar-Mediated Modulation of Soil Microbial Communities and Tobacco Bacterial Wilt Disease. *Appl. Soil Ecol.* **2025**, *206*, 105845. [CrossRef]
72. Liu, H.; Li, X.; Lu, S.; Wang, N.; Li, Y.; Zhang, Y.; Qi, G.; Lu, H.; Dong, H.; Wang, H.; et al. Biennial Biochar Application Mitigates N_2O Emissions in Saline–Alkali Soils by Modulating Microbial Communities and Metabolic Pathways. *Environ. Technol. Innov.* **2025**, *40*, 104475. [CrossRef]
73. Yang, H.; Kerner, P.; Liang, X.; Struhs, E.; Mirkouei, A.; You, Y. Biochar Amendment Modulates Root Metabolome and Rhizosphere Microbiome of Wheat. *Biochar* **2025**, *7*, 46. [CrossRef]
74. Wei, B.; Peng, Y.; Lin, L.; Zhang, D.; Ma, L.; Jiang, L.; Li, Y.; He, T.; Wang, Z. Drivers of Biochar-Mediated Improvement of Soil Water Retention Capacity Based on Soil Texture: A Meta-Analysis. *Geoderma* **2023**, *437*, 116591. [CrossRef]
75. Kang, M.W.; Yibeltal, M.; Kim, Y.H.; Oh, S.J.; Lee, J.C.; Kwon, E.E.; Lee, S.S. Enhancement of Soil Physical Properties and Soil Water Retention with Biochar-Based Soil Amendments. *Sci. Total Environ.* **2022**, *836*, 155746. [CrossRef] [PubMed]
76. Strunecký, O.; Shreedhar, S.; Kolář, L.; Maroušková, A. Changes in Soil Water Retention Following Biochar Amendment. *Energy Sources Part A Recovery Util. Environ. Eff.* **2025**, *47*, 7145–7152. [CrossRef]
77. Santos, J.A.; Gonzaga, M.I.S.; Dos Santos, W.M.; Da Silva, A.J. Water Retention and Availability in Tropical Soils of Different Textures Amended with Biochar. *Catena* **2022**, *219*, 106616. [CrossRef]
78. Peng, L.; Yin, X.; Zi, R.; Fang, Q.; Han, Z.; Zhao, L. Biochar Delays the Downward Water Infiltration and Improves Soil Moisture Retention on Cultivated Sloping Land in the Karst Region. *Soil Tillage Res.* **2026**, *256*, 106839. [CrossRef]
79. Ullah, M.S.; Malekian, R.; Randhawa, G.S.; Gill, Y.S.; Singh, S.; Esau, T.J.; Zaman, Q.U.; Afzaal, H.; Du, D.L.; Farooque, A.A. The Potential of Biochar Incorporation into Agricultural Soils to Promote Sustainable Agriculture: Insights from Soil Health, Crop Productivity, Greenhouse Gas Emission Mitigation and Feasibility Perspectives—A Critical Review. *Rev. Environ. Sci. Biotechnol.* **2024**, *23*, 1105–1130. [CrossRef]
80. Gholamahmadi, B.; Ferreira, C.S.S.; Gonzalez-Pelayo, O.; Bastos, A.C.; Verheijen, F.G.A. Soil Conservation Benefits of Biochar in Mediterranean Vineyards: Enhancing the Soil Sponge Function and Mitigating Water Erosion. *Biochar* **2025**, *7*, 106. [CrossRef]

81. Shi, G.; Cao, X.; Fu, Q.; Li, T.; Chen, Q. Biochar Alleviated Soybean Continuous Cropping Obstacles by Improving Soil Hydrological Properties and Reducing Erosion: Insights from an 11 Year Field Study on Sloping Farmland. *Field Crops Res.* **2026**, *339*, 110348. [CrossRef]
82. Ivanova, N.; Obaeed, G.L.O.; Sulkarnaev, F.; Buchkina, N.; Gubin, A.; Yurtaev, A. Effect of Biochar Aging in Agricultural Soil on Its Wetting Properties and Surface Structure. *Biochar* **2023**, *5*, 75. [CrossRef]
83. Fei, Y.; Liu, Z.; Yi, J.; She, D.; Qiu, W.; Jiang, L.; Liu, M.; Li, S.; Nie, H.; Li, Q.; et al. Biochar Application Enhances Soil Water Storage in Wet Periods but Intensifies Drought Conditions during Dry Periods in Red Soils. *Soil Tillage Res.* **2026**, *256*, 106902. [CrossRef]
84. Yang, Z.; Liu, P.; Wang, S.; Zhang, B.; Li, H.; Wang, X.; Lv, S.; Li, J.; Abdo, A.I.; Wang, L. Optimum Nitrogen Rate Combined with Biochar Increased Wheat Yield While Improving Lodging Resistance. *Eur. J. Agron.* **2026**, *172*, 127849. [CrossRef]
85. Golla, B.; Dechassa, N.; Mohammed, W.; Gezahegn, A.M. Impact of Biochar and Inorganic Fertilizers Rates on Yield and Yield Components of Maize at Bako Western Ethiopia. *J. Agric. Food Res.* **2026**, *26*, 102698. [CrossRef]
86. Dissanayake, L.; Farrar, M.B.; Omidvar, N.; Joseph, S.; Trubenbacher, K.; Hosen, M.H.; Guo, L.; Liu, W.; Bai, Y.; Xu, Z.; et al. Biochar-Based Fertilizer Is Cost-Effective, Reduces Nutrient Input and Improves Nutrient Use Efficiency Without Decreasing Yield. *GCB Bioenergy* **2026**, *18*, e70104. [CrossRef]
87. Meier, S.; De Souza Campos, P.M.; Palma-Millanao, R.; Rojas, N.; González, M.-E.; Muñoz, S.; Ondrasek, G.; Naser, K.; Hirzel, J.; Seguel, A. Biochar-Based Controlled-Release Ammonium Phosphate Fertilizer: Synthesis and Impact on Soil Nutrient Dynamics, Wheat Growth, and Yield under Controlled Conditions. *Environ. Technol. Innov.* **2025**, *39*, 104269. [CrossRef]
88. Shah, G.A.; Mustafa, M.; Asfour, H.Z.; Shoukat, K.; Yasin, A.; Ali, N.; Niazi, M.B.K.; Ondrasek, G.; Rashid, M.I. Nanobiochar-Coating Regulates N and P Release from DAP Fertilizer in Soil and Improves Maize Crop Productivity. *J. Soil. Sci. Plant Nutr.* **2024**, *24*, 6782–6797. [CrossRef]
89. He, H.; Li, M.; Chen, M.; Zhao, L.; Li, Q.; Hu, Z.; Yang, S. Responses of Greenhouse Gas Emissions, Crop Yields, and Soil Properties to Biochar Application of Three Major Cereal Food Crops: A Global Meta-Analysis of Field Studies. *J. Soil. Sci. Plant Nutr.* **2025**, *26*, 609–621. [CrossRef]
90. Fusco, G.M.; Campana, E.; Ciriello, M.; Nicastro, R.; De Paola, F.; De Tommaso, G.; Carillo, P.; Rouphael, Y.; De Pascale, S. Compost and Biochar Synergy Enhances Photosynthetic Efficiency and Antioxidant Responses in Leafy Vegetables under Sub-Optimal Nutrient Supply. *Plant Stress* **2026**, *19*, 101244. [CrossRef]
91. Udomkun, P.; Rupngam, T.; Müller, J.; Boonupara, T.; Kaewlom, P. Effects of Plant-Waste–Derived Biochars on Soil Properties, Biochemical Composition, and Sensory Quality of Water Spinach (*Ipomoea Aquatica* Forsk.). *J. Agric. Food Res.* **2026**, *25*, 102550. [CrossRef]
92. Farhangi-Abriz, S.; Torabian, S.; Qin, R.; Noulas, C.; Lu, Y.; Gao, S. Biochar Effects on Yield of Cereal and Legume Crops Using Meta-Analysis. *Sci. Total Environ.* **2021**, *775*, 145869. [CrossRef]
93. Mei, Y.; Kayoumu, M.; He, T.; Cui, X.; Duan, G. Enhancing Salt Tolerance and Growth of *Oryza Sativa* L. through Biochar-Bacteria Composite Amendment for Potential Application in Coastal Saline Soil Reclamation. *Environ. Technol. Innov.* **2026**, *41*, 104667. [CrossRef]
94. Anwar, T.; Qureshi, H.; El-Beltagi, H.S.; Shokirov, A.; Khudoyberdiyeva, N.; Nurniyazov, A.; Mamarakhimov, O.; Rebouh, N.Y.; Alomran, M.M.; Alsudays, I.M.; et al. Biochar and GA3-Mediated Enhancement of Wheat Performance under Combined Salinity and Drought: Physiological and Biochemical Insights for Resilient Agriculture. *Biodegradation* **2026**, *37*, 4. [CrossRef] [PubMed]
95. Aamer, M.; Zhang, J.; Awan, M.I.; Wei, H.; Nabi, F.; Huang, W.; Liu, Z.; Su, X.; Liu, S.; Elnour, R.O.; et al. Biochar and γ-Aminobutyric Acid Partnership Improves Rice Productivity and Mitigates Sb + Pb Toxicity in Co-Contaminated Soil. *BMC Plant Biol.* **2025**, *26*, 94. [CrossRef] [PubMed]
96. Malik, Z.; Alghanem, S.M.S.; Masood, N.; Rizvi, H.; Waseem, M.; Ali, A.; Alhaithloul, H.A.A.S.; Rizwan, M. Biochar and Montmorillonite in Combination Improved the Plant Growth, Physiology, Yield and Decreased Lead (Pb) Uptake in Wheat (*Triticum aestivum* L.) Under Pb Stress. *J. Soil Sci. Plant Nutr.* **2026**, *26*, 1286–1299. [CrossRef]
97. Algethami, J.S.; Ibrahim, M.; Javed, W.; Alosaimi, E.H.; Irshad, M.K. Efficacy of Fe-BC in Enhancing Growth, Photosynthesis, Nutrition, and Alleviating the Toxicity of Cd and Cr in Rapeseed (*Brassica napus* L.): A Tool for Managing the Environment and Attaining Sustainable Agriculture. *Environ. Technol. Innov.* **2024**, *36*, 103789. [CrossRef]
98. Ibrahim, M.; Li, G.; Tang, Y.-T. Biochar Effects Acidic Soil Remediation and *Brassica oleracea* L. Toxicity—A Case Study in Subtropical Area of China. *Environ. Technol. Innov.* **2021**, *23*, 101588. [CrossRef]
99. Zhang, K.; Tao, R.; Shi, D.; Tong, S.; Chen, L.; Ma, J.; Yan, J.; Li, J.; Yang, R.; Shen, Y. The Role of Biochar Nanoparticles in Reducing Salt Stress in Tomato (*Solanum lycopersicum*) Plants Grown in Fields. *Ind. Crops Prod.* **2024**, *222*, 119775. [CrossRef]
100. Širić, I.; Alhag, S.K.; Al-Shuraym, L.A.; Mioč, B.; Držaić, V.; Abou Fayssal, S.; Kumar, V.; Singh, J.; Kumar, P.; Singh, R.; et al. Combined Use of TiO2 Nanoparticles and Biochar Produced from Moss (*Leucobryum glaucum* (Hedw.) Ångstr.) Biomass for Chinese Spinach (*Amaranthus dubius* L.) Cultivation under Saline Stress. *Horticulturae* **2023**, *9*, 1056. [CrossRef]

101. Simiele, M.; Argentino, O.; Baronti, S.; Scippa, G.S.; Chiatante, D.; Terzaghi, M.; Montagnoli, A. Biochar Enhances Plant Growth, Fruit Yield, and Antioxidant Content of Cherry Tomato (*Solanum lycopersicum* L.) in a Soilless Substrate. *Agriculture* **2022**, *12*, 1135. [CrossRef]
102. Montoya, D.; Fernández, J.A.; Franco, J.A.; Del Carmen Martínez Ballesta, M. Enriched-biochar Application Increases Broccoli Nutritional and Phytochemical Content without Detrimental Effect on Yield. *J. Sci. Food Agric.* **2022**, *102*, 7353–7362. [CrossRef] [PubMed]
103. Suarez, E.; Diaz-Perez, J.C.; Acharya, N.; Cassity-Duffey, K.; Sintim, H.Y.; McAvoy, T. Biochar Rate and Fertilizer Source Influence Tomato Growth, Mortality, Yield, and Profitability. *Horttechnology* **2025**, *35*, 574–583. [CrossRef]
104. De La Rosa, J.M.; Pérez-Dalí, S.M.; Campos, P.; Sánchez-Martín, Á.; González-Pérez, J.A.; Miller, A.Z. Suitability of Volcanic Ash, Rice Husk Ash, Green Compost and Biochar as Amendments for a Mediterranean Alkaline Soil. *Agronomy* **2023**, *13*, 1097. [CrossRef]
105. Turull, M.; Fontàs, C.; Díez, S. Effect of Different Amendments on Trace Metal Bioavailability in Agricultural Soils and Metal Uptake on Lettuce Evaluated by Diffusive Gradients in Thin Films. *Environ. Technol. Innov.* **2021**, *21*, 101319. [CrossRef]
106. Freitas, A.M.; Nair, V.D.; Harris, W.G. Biochar as Influenced by Feedstock Variability: Implications and Opportunities for Phosphorus Management. *Front. Sustain. Food Syst.* **2020**, *4*, 510982. [CrossRef]
107. John, V.; Braga, A.R.D.O.; Danielli, C.K.A.D.O.; Sousa, H.M.; Danielli, F.E.; De Araujo, R.O.; Marques-dos-Santos, C.S.D.C.; Falcão, N.P.D.S.; Guerra, J.F.C. Characterization of Biochar Produced in a Mobile Handmade Kiln from Small-Sized Waste Biomass for Agronomic and Climate Change Benefits. *Agronomy* **2024**, *14*, 1861. [CrossRef]
108. Lund, V.; Salvador, R.; Eriksen, M.L.; Kjærsgaard, N.C.; Hedegaard, M.; Knudby, T. Biochar—A Versatile Outcome of Various Biomasses—Benefits and Challenges. *Eur. J. Sustain. Dev.* **2025**, *14*, 225. [CrossRef]
109. Zhang, X.; Feng, X.; Chai, N.; Kuzyakov, Y.; Zhang, F.; Li, F.-M. Biochar Effects on Crop Yield Variability. *Field Crops Res.* **2024**, *316*, 109518. [CrossRef]
110. Singh, H.; Northup, B.K.; Rice, C.W.; Prasad, P.V.V. Biochar Applications Influence Soil Physical and Chemical Properties, Microbial Diversity, and Crop Productivity: A Meta-Analysis. *Biochar* **2022**, *4*, 8. [CrossRef]
111. Hoque, M.M.; Saha, B.K.; Scopa, A.; Drosos, M. Biochar in Agriculture: A Review on Sources, Production, and Composites Related to Soil Fertility, Crop Productivity, and Environmental Sustainability. *C* **2025**, *11*, 50. [CrossRef]
112. Yeboah, E.; Asamoah, G.; Ofori, P.; Amoah, B.; Agyeman, K.O.A. Method of Biochar Application Affects Growth, Yield and Nutrient Uptake of Cowpea. *Open Agric.* **2020**, *5*, 352–360. [CrossRef]
113. Chiaramonti, D.; Lotti, G.; Tozzi, F.; Casini, D.; Vaccari, F.P.; Sanei, H.; Luconi, M.; Buffi, M. Is Soil Sampling Appropriate for Quantitative Carbon Accounting for Biochar? An Experimental Investigation to Assess Soil Carbon Accumulation. *Biomass Bioenergy* **2026**, *205*, 108537. [CrossRef]
114. Schmidt, H.; 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]
115. Köves, M.; Madár, V.; Ringer, M.; Kocsis, T. Overview of Traditional and Contemporary Industrial Production Technologies for Biochar along with Quality Standardization Methods. *Land* **2024**, *13*, 1388. [CrossRef]
116. Divyangkumar, N.; Panwar, N.L. Standardization, Certification, and Development of Biochar Based Fertilizer for Sustainable Agriculture: An Overview. *Environ. Pollut. Manag.* **2024**, *1*, 186–202. [CrossRef]
117. John, V.; Braga, A.R.D.O.; Danielli, C.K.A.D.O.; Sousa, H.M.; Danielli, F.E.; Falcão, N.P.D.S.; Guerra, J.; Lasmar, D.J.; Marques-dos-Santos, C.S.C. Investigation, Prospects, and Economic Scenarios for the Use of Biochar in Small-Scale Agriculture in Tropical. *Agriculture* **2025**, *15*, 1700. [CrossRef]
118. Zilberman, D.; Laird, D.; Rainey, C.; Song, J.; Kahn, G. Biochar Supply-Chain and Challenges to Commercialization. *GCB Bioenergy* **2023**, *15*, 7–23. [CrossRef]
119. Ganzi, G.; Pronti, A. Cost–Benefit Analysis of Biochar Production: The Case Study of an Abandoned Rural Site, Borgo Di Perolla, in Tuscany, Italy. *Biomass* **2026**, *6*, 19. [CrossRef]
120. Kumar, A.; Bhattacharya, T.; Shaikh, W.A.; Roy, A.; Chakraborty, S.; Vithanage, M.; Biswas, J.K. Multifaceted Applications of Biochar in Environmental Management: A Bibliometric Profile. *Biochar* **2023**, *5*, 11. [CrossRef]
121. Xiang, L.; Liu, S.; Ye, S.; Yang, H.; Song, B.; Qin, F.; Shen, M.; Tan, C.; Zeng, G.; Tan, X. Potential Hazards of Biochar: The Negative Environmental Impacts of Biochar Applications. *J. Hazard. Mater.* **2021**, *420*, 126611. [CrossRef] [PubMed]
122. Brtnicky, M.; Datta, R.; Holatko, J.; Bielska, L.; Gusiatin, Z.M.; Kucerik, J.; Hammerschmiedt, T.; Danish, S.; Radziemska, M.; Mravcova, L.; et al. A Critical Review of the Possible Adverse Effects of Biochar in the Soil Environment. *Sci. Total Environ.* **2021**, *796*, 148756. [CrossRef] [PubMed]
123. Dong, M.; Jiang, M.; He, L.; Zhang, Z.; Gustave, W.; Vithanage, M.; Niazi, N.K.; Chen, B.; Zhang, X.; Wang, H.; et al. Challenges in Safe Environmental Applications of Biochar: Identifying Risks and Unintended Consequence. *Biochar* **2025**, *7*, 12. [CrossRef]
124. Wang, L.; Deng, J.; Yang, X.; Hou, R.; Hou, D. Role of Biochar toward Carbon Neutrality. *Carbon Res.* **2023**, *2*, 2. [CrossRef]

125. Khan, S.; Irshad, S.; Mehmood, K.; Hasnain, Z.; Nawaz, M.; Rais, A.; Gul, S.; Wahid, M.A.; Hashem, A.; Abd_Allah, E.F.; et al. Biochar Production and Characteristics, Its Impacts on Soil Health, Crop Production, and Yield Enhancement: A Review. *Plants* **2024**, *13*, 166. [CrossRef] [PubMed]
126. Lyu, J.; Zimmerman, A.R. Large Losses of Pyrogenic Carbon (Biochar) and Native Soil Carbon During a 15-Month Field Study in North Florida, USA. *Agriculture* **2025**, *15*, 300. [CrossRef]
127. Schmidt, H.; Abiven, S.; Cowie, A.; Glaser, B.; Joseph, S.; Kammann, C.; Lehmann, J.; Leifeld, J.; Pan, G.; Rasse, D.; et al. Biochar Permanence—A Policy Commentary. *GCB Bioenergy* **2025**, *17*, e70092. [CrossRef]