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Biochar

REVIEW

Soil health response to biochar combined with other amendments: a review

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Abstract

Co-application of biochar with other amendments is generating interest as a means to increase biochar effectiveness for improving soil health. Yet, the extent to which such co-application improves soil health is unclear. This paper (i) synthesized the impact of biochar applied with or without organic and inorganic amendments on soil health indicators including soil physical, chemical, and biological properties using field studies, (ii) discussed potential factors that may affect the performance of the co-application, and (iii) summarized research needs. Based on 28 peer-reviewed publications up to September 30, 2024, biochar co-application improved 9 of 16 soil properties compared to biochar alone. It enhanced wet aggregate stability in 5 of 9 comparisons by 45%, saturated hydraulic conductivity in 5 of 6 by 17%, field water content in 8 of 14 by 20%, cation exchange capacity in 9 of 17 by 58%, and organic matter concentration in 5 of 9 by 37%. Also, co-application of biochar increased soil microbial biomass C, phosphatase activity, and N and P concentrations by 33% to 76% in most comparisons. However, it had mixed effects on bulk density, pH, electrical conductivity, C and K concentrations, as well as urease and dehydrogenase activities. Biochar co-application with organic amendments (compost/manure) improved soil physico-chemical properties (bulk density, C, N, P, K) more consistently than with inorganic amendments (NPK). The benefits of biochar co-application increased with higher application rates. These findings suggest that biochar co-application can improve selected soil properties more than biochar alone, with benefits for soil structure, water retention, nutrient availability, and microbial activity, though results for some properties remain inconsistent. Long-term studies (>5 years) across diverse soils and climates are needed to further elucidate these effects and optimize biochar co-application strategies for sustainable soil management.

Highlights

- Biochar co-applied with amendments (compost/manure/NPK) improves some soil properties over biochar alone
- Soil benefits increase with an increase in biochar co-application rate
- Biochar + organic amendments are more effective than biochar + inorganic amendments

Keywords Biochar, Compost, Fertilizer, Manure, Soil properties, Soil health

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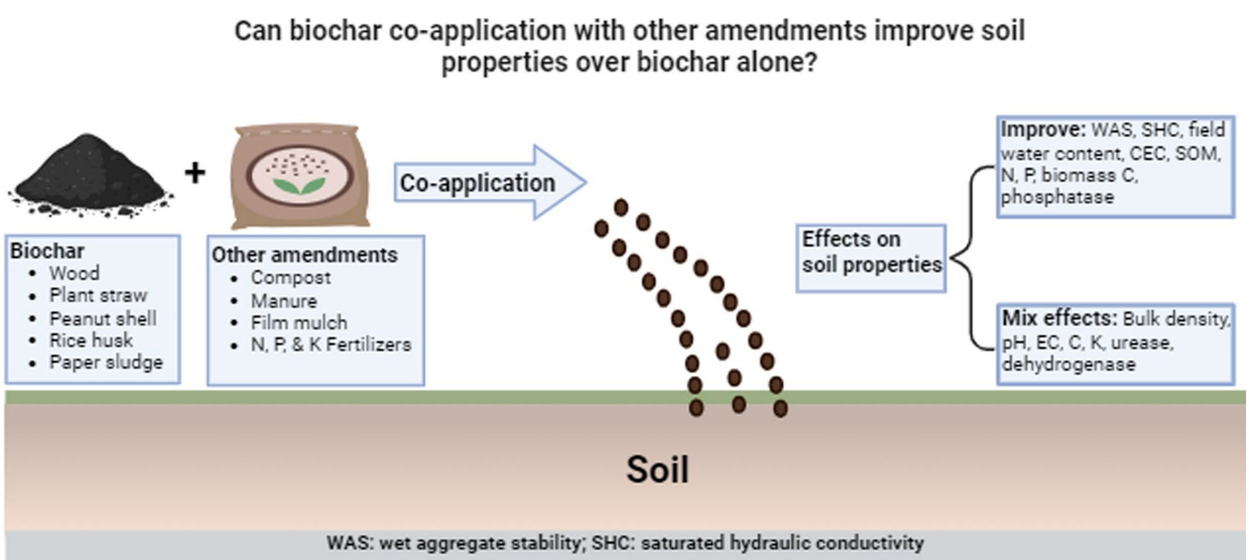
Graphical Abstract



1 Introduction

Soil health is a critical determinant of the overall well-being of ecosystems, agricultural productivity, and environmental sustainability (Lehmann et al. 2020). It is shaped by a complex interplay of physical, chemical, and biological properties that regulate plant growth, nutrient cycling, water movement, and microbial dynamics (Fierer et al. 2021; Lehmann et al. 2020). However, soil health is increasingly threatened by intensive land use, climate variability (e.g., extreme rainfall, drought, and heat waves), and unsustainable management practices. To address these challenges, there is a growing need for effective soil management strategies that can sustainably restore and enhance soil function.

Biochar, a porous carbon-rich material produced via pyrolysis of biomass under limited oxygen, has gained attention as a promising amendment for improving soil health (Lehmann et al. 2011). Biochar's key characteristics, such as high surface area, cation exchange capacity, and long-term stability, enable it to influence soil physical structure, enhance nutrient retention, and support microbial activity (Bai et al. 2022; Lehmann et al. 2011; Qi et al. 2024). The mechanisms by which biochar improves soil properties include increasing water holding capacity, reducing bulk density, buffering pH, and supplying or adsorbing nutrients (Ding et al. 2016).

Despite these attributes, the soil health benefits of biochar vary widely depending on feedstock type, pyrolysis conditions, application rate, soil texture, pH, and climate (Blanco-Canqui 2021; El-Naggar et al. 2019; He et al. 2021; Premalatha et al. 2023; Singh et al. 2022). For example, wood or crop residue biochar can cause N immobilization due to its low nutrient concentration (El-Naggar et al. 2019; Jeffery et al. 2011). Further, a review by Blanco-Canqui (2021) indicated that biochar application improved most soil physical properties but had little or no effect on water and wind erosion. A meta-analysis by Singh et al. (2022) indicated that biochar application improved soil properties more in coarse- and fine-textured soils than in medium-textured soils. Additionally, Premalatha et al. (2023) highlighted in a review that biochar is more effective in acidic soils than in alkaline or calcareous soils. Yet another review showed that biochar improved soil fertility and increased crop yields in the tropics but not in temperate soils (Jeffery et al. 2017). These inconsistencies highlight the need to optimize biochar use through synergistic practices.

A potential strategy to boost biochar effectiveness could be the combination of biochar with organic or inorganic amendments. This approach aims to leverage the synergistic benefits of biochar stability and sorption potential with the nutrient richness of compost, manure, or mineral fertilizers (Agegnehu et al. 2017; Lehmann et al. 2020). For instance, biochar can reduce nutrient leaching from fertilizers and enhance nutrient-use efficiency, while organic amendments can supply labile C and stimulate microbial processes. Together, biochar and other amendments may enhance both short-term fertility and long-term soil function, particularly in degraded or sandy soils (Agegnehu et al. 2017; Bai et al. 2022; Naeem et al. 2018; Qian et al. 2023). However, the effects of biochar co-application with various amendments on soil properties remain poorly understood.

The effects of biochar co-application on soil health indicators can vary depending on soil properties, climatic conditions, biochar and amendment type, and application amount (Bai et al. 2022; Naeem et al. 2018). While previous reviews (Agegnehu et al. 2017; Qian et al. 2023; Zahra et al. 2021) have examined the effects of biochar-compost mixtures on soil properties, none have systematically evaluated biochar co-application with a broad range of organic and inorganic amendments. Furthermore, most meta-analyses have focused on crop yield responses (Bai et al. 2022; Ye et al. 2020), leaving a knowledge gap in how biochar co-application affects soil physical, chemical, and biological properties holistically.

To systematically evaluate the variable effects of biochar co-application, we employ a cause-evidence-impact framework (Balaganesh et al. 2022; Manea et al. 2024). This approach examines how specific co-application practices (cause) influence measurable soil properties (evidence) and ultimately affect functional soil health outcomes (impact). By establishing these mechanistic linkages, the framework helps interpret variable findings and guides the design of context-specific biochar co-application strategies. To guide this synthesis, we posed the following research questions: (1) How does biochar co-application with organic or inorganic amendments affect soil physical, chemical, and biological properties compared to biochar alone? (2) What environmental and management factors condition the effectiveness of biochar co-application on soil health outcomes? (3) Where do research gaps remain in understanding the mechanisms and long-term impacts of biochar co-application on soil systems? Therefore, the objectives of this review are to: (i) synthesize the impact of biochar applied with or without organic and inorganic amendments on soil health indicators using field studies, (ii) discuss potential factors that may affect the performance of the co-application, and (iii) summarize research needs.

2 Methods

2.1 Literature search and selection criteria

We reviewed literature on the impact of co-application of biochar on soil properties up to September 30, 2024, using Web of Science and Google Scholar. The search terms combined the keyword "biochar" with terms related to amendments, such as "amendment", "organic fertilizer", "inorganic fertilizer", "animal manure", "compost", and "polyacrylamides". These were further combined with terms related to soil properties, including "soil properties", "bulk density", "aggregate stability", "water infiltration", "hydraulic conductivity", "water content", "C", "organic matter", "electrical conductivity" (EC), "cation exchange capacity" (CEC), "pH", "N", "P", "K", and "biological properties". Boolean operators (AND/OR) were applied to refine the searches and ensure a comprehensive review.

To ensure the quality and relevance of the included studies, we applied the following inclusion criteria: (a) manuscripts must be peer-reviewed and written in English, (b) studies must involve field experiments (laboratory and greenhouse studies were excluded), (c) treatments must include a control (neither biochar nor amendment), biochar alone, amendment alone, and biochar + amendment, and (d) standard methods must be used for the characterization of soil properties. Studies were excluded if they: (a) lacked the specified treatments, (b) were review articles or meta-analyses, (c) did not focus on soil property responses, or (d) provided insufficient data for analysis. Based on these criteria, we identified 28 peer-reviewed manuscripts for inclusion in the review. A structured framework was developed to guide the review process, including search strategy, study selection, data extraction, classification, quality assessment, and evaluation of treatment effects (Fig. 1).

2.2 Data management and extraction protocols

Data on soil properties were extracted and summarized in tables, detailing study location, soil texture, crop species, experiment duration, biochar feedstock, biochar production condition and rate, and amendment type and rate (Tables S1–S10). For studies that reported data in graphical form, WebPlotDigitizer (Rohatgi 2021) was used to extract numerical values. To ensure accuracy, all extracted data were cross-validated with the reported text, tables, and figures in the original publications. To enable comparisons across studies, all soil property data were standardized to common units. When multiple years of data were available, we selected the most recent year, except when authors reported multi-year averages. In cases where studies from the same trial were published at different times (e.g., 1 vs. 3 years), only the most recent publication was included to avoid duplication. For studies with multiple treatments, each combination of biochar and amendment rates was treated as a separate comparison.

The dataset was further analyzed through subgroup comparisons to explore patterns in biochar co-application effects. We grouped soil textural classes in coarse-, medium-, and fine-textured soils. Coarse-textured soils included sand, sandy loam, and sandy clay loam; medium-textured soils included loam and silt loam; and fine-textured soils included clay and clay loam. The literature reviewed showed that the following amendments were combined with biochar: animal manure (hereafter

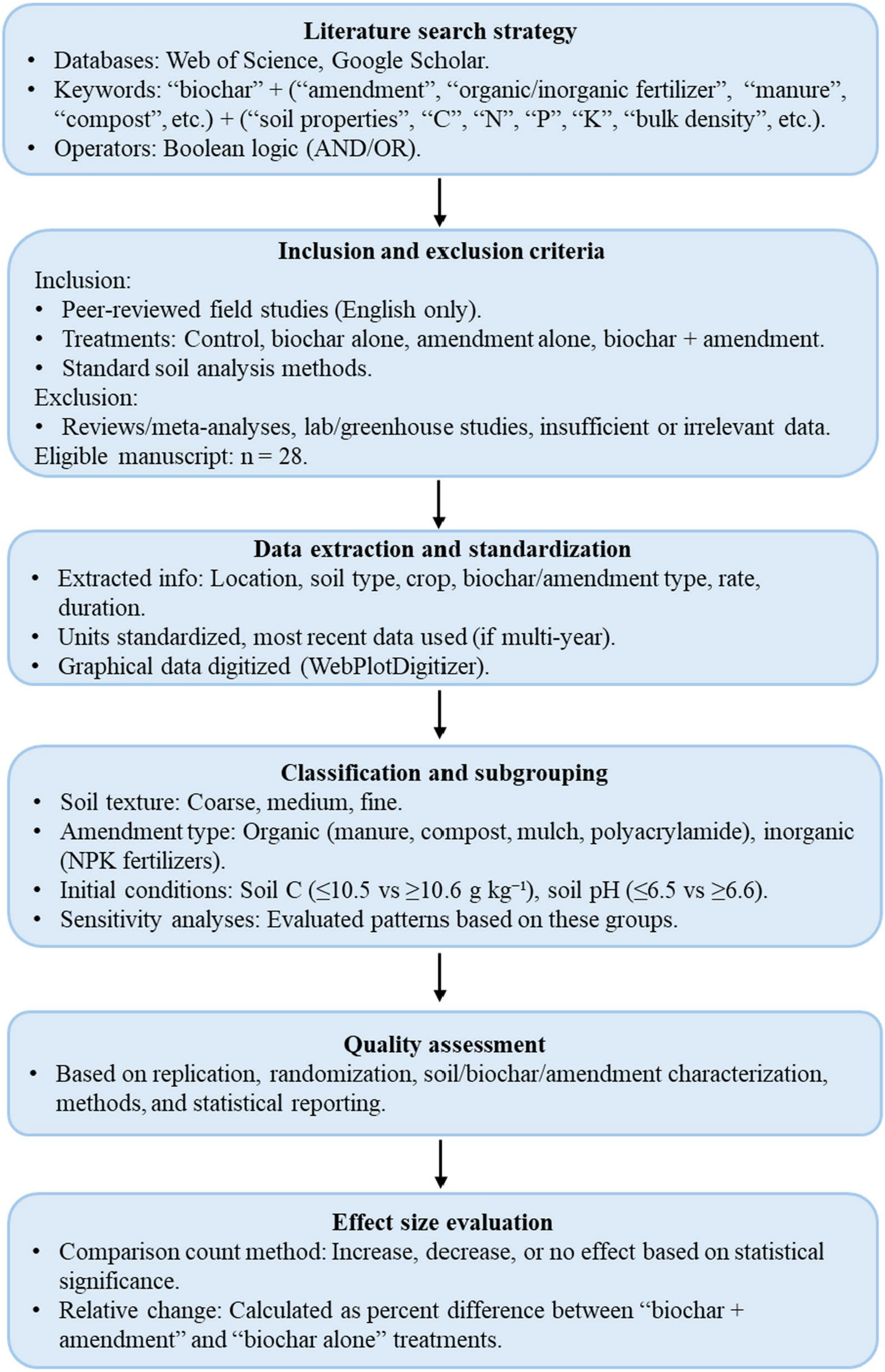


Fig. 1 Overview of the methodological framework used to review and categorize field studies on the effects of biochar co-application with amendments on soil health indicators

referred to as manure), compost, film mulch, polyacrylamide, and N, P, and K fertilizers. These amendments were grouped into organic amendments (manure, compost, film mulch, and polyacrylamide) and inorganic amendments (N, P, and K fertilizers) categories to assess their distinct impacts. Additional subgroup analyses included initial soil C concentrations (≤10.5 vs. ≥10.6 g kg^{-1}) and initial soil pH (≤6.5 vs. ≥6.6). Sensitivity analyses were conducted by grouping studies based on amendment type, soil texture, and initial soil C and pH conditions to assess the consistency of biochar co-application effects.

2.3 Quality assessment criteria

The quality of the selected studies was evaluated based on several factors. Experimental design was assessed in terms of replication, randomization, and the inclusion of appropriate control treatments. Soil characterization was examined to ensure that studies provided essential background information, including soil texture, initial pH, and initial C concentration. The description of biochar and amendment properties was reviewed to confirm that details on biochar feedstock, pyrolysis temperature, amendment type, and application rates were included. Measurement methods were evaluated to ensure adherence to standardized protocols for soil property analysis.

To evaluate the effects of biochar co-application on soil properties, we included only studies that reported statistical comparisons (e.g., *p*-values, ANOVA, or other post-hoc tests), ensuring all findings reflected statistically validated treatment effects. Descriptors such as "increase," "decrease," or "no effect" were assigned based on the authors' reported statistical test outcomes (e.g., ANOVA, Tukey's test). We did not perform independent statistical tests but relied on the interpretations provided in the original studies. Studies lacking essential methodological details were excluded to ensure the reliability of the findings.

2.4 Effect size calculation

The effect of biochar co-application on soil properties was evaluated using a comparison count approach. Each soil property response was categorized as an increase, decrease, or no effect. Statistical significance, as reported in the original studies, was used to determine whether biochar co-application had a meaningful impact. Comparisons where significant differences were observed were classified as either an increase or decrease, depending on the direction of change, while those without significant differences were categorized as no effect. If the number of comparisons for a given soil property across all the published studies followed the pattern of increase > decrease > no effect, biochar co-application was interpreted as increasing that property in most cases. This method accounted for multiple biochar and amendment rate combinations within individual studies, ensuring that only statistically supported findings were considered. However, the absence of precise variance measures in most published studies limited the feasibility of calculating weighted effect sizes.

To further quantify changes in soil properties, relative percent differences between biochar co-application (BC + A) and biochar alone (BC) were calculated using Eq. 1:

$$\text{Change (\%)} = \left(\frac{(\text{BC} + \text{A} - \text{BC})}{\text{BC}}\right) \times 100 \quad (1)$$

where BC + A is the measured value under biochar co-application and BC is the value under biochar alone.

Comparison count was chosen over meta-analysis due to the limited number of studies available for many soil properties (Table 1) and the lack of variance measures in approximately 70% of the reviewed studies, which are essential for calculating effect sizes (Borenstein et al. 2021). Additionally, the studies exhibited significant heterogeneity in key factors, including soil types (e.g., sandy, loamy, clayey), amendment types and rates (e.g., compost, manure, inorganic fertilizers), and experimental conditions (e.g., management practices). This variability makes it difficult to pool data meaningfully for meta-analysis. Despite these limitations, the comparison count method provided a systematic and transparent approach to assess the frequency and direction of biochar co-application effects, offering insights into the trends observed across the literature.

Table 1 summarizes the studies and comparisons on the effects of biochar co-application on soil properties.

3 Impact of co-application of biochar with amendment on soil properties

3.1 Soil physical properties

3.1.1 Bulk density

Bulk density is an important soil health indicator as it affects soil compaction, water infiltration, soil aeration, root growth, and many other processes, which influence soil functioning and crop productivity (Blanco-Canqui 2017; Omondi et al. 2016). For instance, a reduction in bulk density value following co-application of biochar with amendments would suggest reduced soil compaction (Blanco-Canqui 2017). We analyzed 17 studies on bulk density response to biochar co-application, which resulted in 30 comparisons (Table 1). Co-application of biochar reduced bulk density in 14 of 30 comparisons (47%) and had no effect in the remaining 53% (Fig. 2). In comparisons showing reduction, bulk density decreased by an average of 12% (1.3 vs. 1.2 Mg m^{-3}) (Table 1). These results suggest that mixing biochar with other

Table 1 Summary of studies and comparisons on the effects of biochar co-application on soil properties

Soil property	Number of studies	Number of comparisons	Cases of improvement with biochar co-application*	Average change due to biochar co-application†%
Physical				
Bulk density	17	30	14 of 30	12
Wet aggregate stability	4	9	5 of 9	45
Saturated hydraulic conductivity	3	6	5 of 6	17
Field water content	6	14	8 of 14	20
Chemical				
Soil C	14	27	11 of 27	21
Organic matter	4	9	5 of 9	37
pH	17	35	9 of 35	12
Cation exchange capacity	7	17	9 of 17	58
N	16	26	14 of 26	33
P	14	24	15 of 24	76
K	11	18	9 of 18	64
Electrical conductivity	8	10	3 of 10	16
Biological				
Microbial biomass C	4	7	5 of 7	43
Urease	2	4	2 of 4	12
Dehydrogenase	2	4	2 of 4	19
Phosphatase	3	5	3 of 5	63

*Number of comparisons in which biochar co-application improved soil property over biochar alone

† Average percentage change quantifying the extent of this improvement

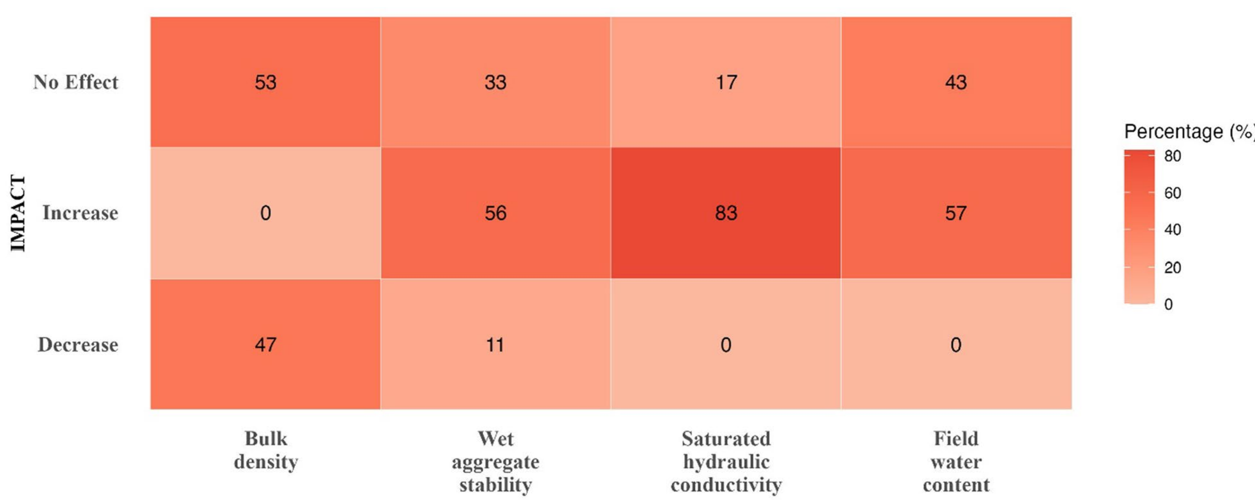


Fig. 2 Summary of biochar co-application impacts on soil physical properties compared to biochar alone. Each column represents a soil physical property, while the rows indicate the percentage of impacts categorized as Increase, Decrease, or No Effect. The color gradient highlights the relative magnitude of these impacts

amendments does not improve the ability of biochar to reduce soil bulk density in about half of cases.

The limited or no response of soil bulk density to biochar co-application in the 53% of cases could be due to similarities in bulk densities between biochar and amendments and variability in data. Complex interactions among biochar and amendment types, and application rates may also lead to nullifying or counteractive effects on bulk density (Agegnehu et al. 2017; Kang et al. 2018). Additionally, soil characteristics such as texture, structure, and microbial activity are crucial in determining bulk density responses (Agegnehu et al. 2017), which vary across studies. These factors will be discussed in more detail later in this paper.

The observed reduction in bulk density can be attributed to two key mechanisms. First, biochar (<0.6 Mg m^{-3}) and organic amendments such as compost (0.42–0.65 Mg m^{-3}) (Khater 2015) and animal manure (0.9–0.14 Mg m^{-3}) (Pop et al. 2019) have lower bulk densities than the typical agricultural soils (1.25 Mg m^{-3}). Thus, the combined application of biochar and amendments with low bulk densities can reduce the bulk density of the whole soil via a mixing and dilution effect (Blanco-Canqui 2017; Lehmann et al. 2011). Second, biochar and amendments can synergistically interact with soil particles to improve aggregation, increase porosity, and reduce bulk density (Qian et al. 2023). Indeed, Somerville et al. (2020) found that co-applying wood biochar with compost increased wet aggregate stability and reduced soil bulk density relative to biochar alone. These reductions in bulk density, observed in nearly half of the comparisons, can enhance root growth, aeration, and water movement. However, the inconsistent effects across studies suggest that the benefits of biochar co-application are context-dependent and may be more pronounced in coarse-textured or degraded soils where structural improvement is needed.

3.1.2 Wet aggregate stability

Stable soil aggregates reduce soil erodibility, protect soil C, promote C and nutrient storage, macroporosity, and drainage, and improve other vital soil processes (Haydu-Houdeshell et al. 2018). Four studies evaluated the effects of biochar co-application on soil wet aggregate stability, resulting in 9 comparisons (Table 1). Biochar co-application increased wet aggregate stability in 5 of 9 comparisons (56%), decreased it in 1 of 9 (11%), and had no effect in 3 of 9 (33%) (Fig. 2). Where increases occurred, aggregate stability improved by an average of 45% (83.8 vs. 127.7 g kg^{-1}) (Table 1). This suggests that biochar co-application can enhance wet aggregate stability in most cases.

Biochar co-application likely increased wet aggregate stability through improvements in soil physico-chemical properties (Ibrahim et al. 2019; Somerville et al. 2020). For example, adding organic amendments (e.g., manure) may supply labile organic binding agents that facilitate the binding of biochar and mineral particles into stable aggregates (Khademalrasoul et al. 2014). This synergetic interaction supports the agglomeration of organic and inorganic particles to form strong aggregates and improve soil structure. The implications of increased wet aggregate stability are significant, particularly for erosion-prone soils and areas with high rainfall variability. These improvements suggest the potential of biochar co-application to enhance soil structural stability and support better water retention and climate resilience.

3.1.3 Saturated hydraulic conductivity

Soil hydraulic conductivity refers to the ease with which water can move through the soil (Zhang and Schaap 2019). Similar to wet aggregate stability, few studies reported the impact of biochar co-application on soil hydraulic conductivity (Table 1). Only 3 studies (6 comparisons) were available, and all reported saturated hydraulic conductivity and not unsaturated hydraulic conductivity (Table S2). Biochar co-application increased saturated hydraulic conductivity in 5 of 6 comparisons (83%) and had no effect in the remaining 17% (Fig. 2). In the comparisons reporting an increase, saturated conductivity improved by an average of 17% (6.9 vs. 7.9 mm h^{-1}) (Table 1).

The observed increases are likely due to improved soil structural properties from the synergistic effects of biochar co-application, such as enhanced aggregate stability (Ibrahim et al. 2019) and macroporosity (Ayaz et al. 2022). Notably, biochar co-application improved wet aggregate stability in most comparisons (Table 1; Fig. 2), which likely contributed to greater pore connectivity and water movement. However, not all studies reporting saturated hydraulic conductivity included data on soil aggregate stability or macroporosity, limiting our ability to establish a clear correlation.

The observed increases in saturated hydraulic conductivity have important implications for water management in agricultural systems. Enhanced hydraulic conductivity facilitates water infiltration, reduces waterlogging, and minimizes surface runoff, which are critical for optimizing irrigation and mitigating drought stress (Zhang and Schaap 2019). However, in unsaturated conditions, which dominate most agricultural settings, increased conductivity may accelerate nutrient leaching, particularly in coarse soils or high-rainfall environments (Biederman and Harpole 2013; Laird et al. 2010; Usowicz and Lipiec 2021). These potential trade-offs underscore the need for a more comprehensive understanding of water dynamics under both saturated and unsaturated conditions. Given the complexity of water flow in field soils, future studies should assess both saturated and unsaturated conductivity, along with leaching and structural indicators, to inform optimal biochar-amendment strategies.

3.1.4 Field water content

Soil management practices that improve soil water storage are crucial for sustaining crop production, particularly in water-limited environments. Would biochar

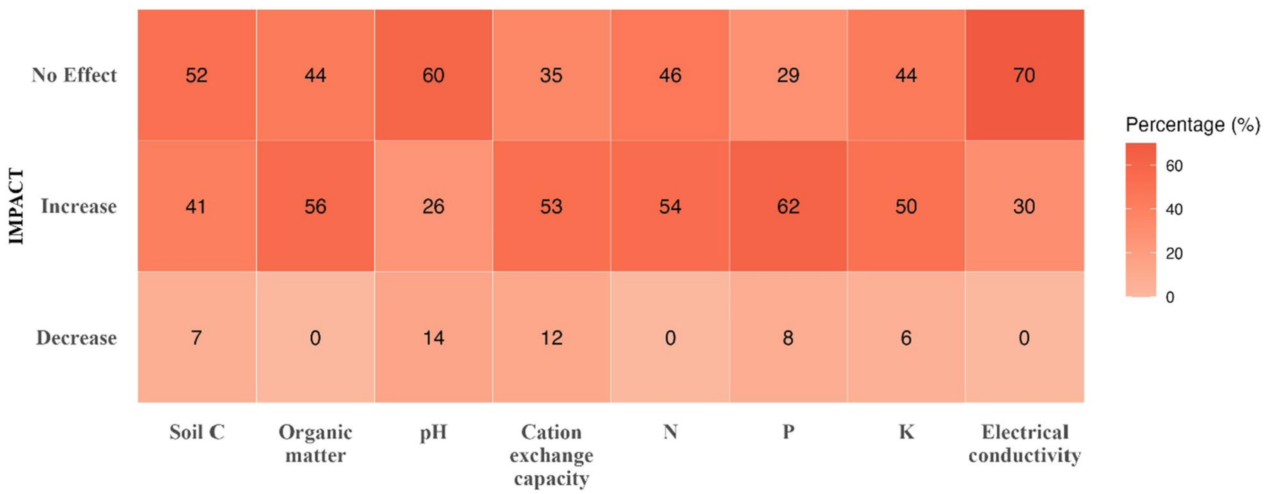


Fig. 3 Summary of biochar co-application impacts on soil chemical properties as compared with biochar alone. Each column represents a soil chemical property, while the rows indicate the percentage of impacts categorized as Increase, Decrease, or No Effect. The color gradient highlights the relative magnitude of these impacts

co-application improve biochar effectiveness for water storage and conservation? Only one study examined biochar co-application impacts on soil plant available water, which is the difference in volumetric water content between field capacity (−33 kPa) and permanent wilting point (−1500 kPa). The lone study (Somerville et al. 2020) found no effect of biochar co-application on plant available water. However, more studies (6 studies for 14 comparisons) reported field water content (Table 1), which is the total amount of water present in the soil. Biochar co-application increased field water content in 8 of 14 comparisons (57%) and had no effect in the remaining 6 comparisons (43%) (Fig. 2). Among the cases showing an increase, water content rose by an average of 20% (15.9 vs. 18.9%) (Table 1).

Biochar co-application increased field water content more than biochar alone likely due to improvements in soil structure and moisture retention. For example, biochar co-application improved wet aggregate stability and hydraulic conductivity in 56% and 83% of comparisons, respectively (Fig. 2), which could contribute to better soil water storage. Additionally, when mixed, the relatively large surface area of biochar and the organic matter input from amendments such as manure can synergistically increase sorption capacity and water retention in soil (Adekiya et al. 2019; Rajapaksha et al. 2016; Zahra et al. 2021). Similar findings were reported in previous reviews, which showed that biochar co-application with compost improved soil water retention across various soil types and climates (Qian et al. 2023; Zahra et al. 2021). Additionally, meta-analyses (Blanco-Canqui 2017; Omondi et al. 2016) highlighted that biochar alone can improve water holding capacity, particularly in sandy soils, suggesting that co-application with organic amendments could further amplify these effects.

These findings suggest that biochar co-application has considerable potential for enhancing soil water content, thereby supporting water storage and soil resilience. This improvement is particularly valuable for mitigating drought stress and optimizing irrigation in water-limited regions, where even small increases in water retention can have significant agricultural benefits. However, further research is needed to clarify how biochar co-application affects plant-available water across different soil types and climatic conditions.

3.2 Soil chemical properties

3.2.1 Soil carbon

Increasing soil C concentration is crucial for enhancing soil health, agricultural productivity, and environmental sustainability. Soil C plays an essential role in enhancing aggregate stability, increasing water retention, and supporting microbial activity by serving as a food and energy source (Sarma et al. 2018; Trivedi et al. 2018). Organic C, primarily derived from plant residues, root exudates, manure, compost, and biochar, forms the foundation of soil structure and nutrient cycling (Lehmann et al. 2020).

Fourteen studies provided 27 comparisons on the effects of biochar co-application on soil C concentration (Table 1). Biochar co-application increased soil C in 41% of comparisons (11 of 27), had no effect in 52% (14 of 27), and decreased it in 7% (2 of 27) (Fig. 3). In comparisons showing an increase, soil C rose by an average of 7 g kg^{-1} (0.7% C). These results indicate that mixing biochar with other amendments may not increase soil C concentration more than biochar alone.

The lack of response to biochar co-application in 52% of cases is likely due to differences in the quality and stability of C inputs. Biochar, composed of highly aromatic and stable C compounds (25% to 95% C content), contributes persistent C pools, whereas many organic amendments (e.g., compost, manure) contain labile C that is prone to microbial mineralization (Blanco-Canqui 2021; Liu et al. 2016). The limited response may also be attributed to low overall C input from amendments relative to biochar. For instance, some amendments (e.g., N, P, and K fertilizers) do not contribute C to the soil, while others (e.g., manure, compost) add less chemically stable C compared to biochar. In contrast, the increase in soil C concentration observed in 41% of comparisons may result from the synergistic addition of stable C from biochar and labile C from organic amendments. These interactions likely influence C transformation pathways. The combination may stimulate microbial activity and root growth, thereby indirectly increasing C inputs and enhancing soil aggregation (Qian et al. 2023; Zhou et al. 2023).

However, this synergism can also induce positive priming effects, wherein the addition of easily decomposable C stimulates microbial decomposition of native soil organic matter, leading to net C losses (Bai et al. 2022; Ding et al. 2018). For example, microbial respiration may increase due to the sudden influx of energy-rich substrates, accelerating soil organic matter mineralization and CO_2 release. This may explain the observed decreases in soil C reported in 7% of the studies. Additionally, biochar co-application can alter microbial C use efficiency and enzyme activity, further influencing C turnover and stabilization (Wang et al. 2023; Zhang et al. 2023). These findings show the importance of balancing labile and recalcitrant C inputs to prevent unintended mineralization. Future research should investigate the interactions between biochar and labile C sources on microbial-mediated C transformations, aggregate formation, and the stabilization of different soil C pools (labile, particulate, and mineral-associated). Understanding these mechanisms is essential for optimizing biochar co-application use in C sequestration and climate mitigation strategies.

3.2.2 Soil organic matter

Soil organic matter is a broader measure of decomposed and partially decomposed organic materials, comprising approximately 58% organic C along with essential elements like N, P, S, and various functional groups (Bot and Benites 2005; Lehmann et al. 2020). Unlike soil C, which is often measured as total organic C, soil organic matter reflects the dynamic pool of humic substances, microbial biomass, and partially stabilized residues that actively influence soil biological, chemical, and physical processes (Celestina et al. 2019; Fischer and Glaser 2012).

Our review identified 4 studies (9 comparisons) evaluating biochar co-application effects on soil organic matter (Table 1). Biochar co-application increased soil organic matter concentration in 56% of comparisons (5 of 9) and had no effect in the remaining 44% (Fig. 3). In comparisons reporting increases, soil organic matter rose by about 6 to 20 g kg^{-1}, indicating that combining biochar with amendments can enhance soil organic matter more effectively than biochar alone.

The type of amendment used is a key determinant of soil organic matter changes. Biochar co-applied with compost or manure led to increased soil organic matter in 5 of 6 comparisons, whereas inorganic amendments had less effect (Fig. 4a, Appendix; Table S5). Organic amendments supply labile organic matter and nutrients, which may be physically protected and chemically stabilized by biochar porous structure and surface functional groups, thereby enhancing soil organic matter retention (Agegnehu et al. 2017; Zahra et al. 2021). For example, a review by Qian et al. (2023) reported that biochar-compost combinations reduced soil organic matter mineralization rates in tropical soils, while Zhou et al. (2023) showed that co-composted biochar increased soil organic matter content by nearly 99%. These studies suggest that stabilization mechanisms such as organo-mineral complex formation, pore entrapment, and chemical bonding contribute to greater soil organic matter preservation when biochar is co-applied with organic materials.

Importantly, while soil organic matter and soil C are interrelated, they are not always correlated, as shown in Fig. 3. The disconnect could be due to differences in measurement, transformation dynamics, and the proportion of stabilized versus labile fractions (Celestina et al. 2019; Zhou et al. 2023). Therefore, future research should explore how soil organic matter and soil C respond differently to co-application under varying management practices and environmental conditions. Based on limited data, the literature indicates that biochar co-application particularly with compost or manure can enhance soil organic matter more than biochar alone. This improvement can significantly benefit soil fertility, water retention, and microbial function, particularly in tropical and degraded soils.

3.2.3 Soil pH

Soil pH, a critical determinant of nutrient availability and plant growth, regulates microbial activity and biochemical processes in soils. Our review analyzed 17 studies (35 comparisons) comparing soil pH between biochar alone and biochar co-application (Table 1). Biochar co-application had no effect on soil pH in 60% of comparisons (21

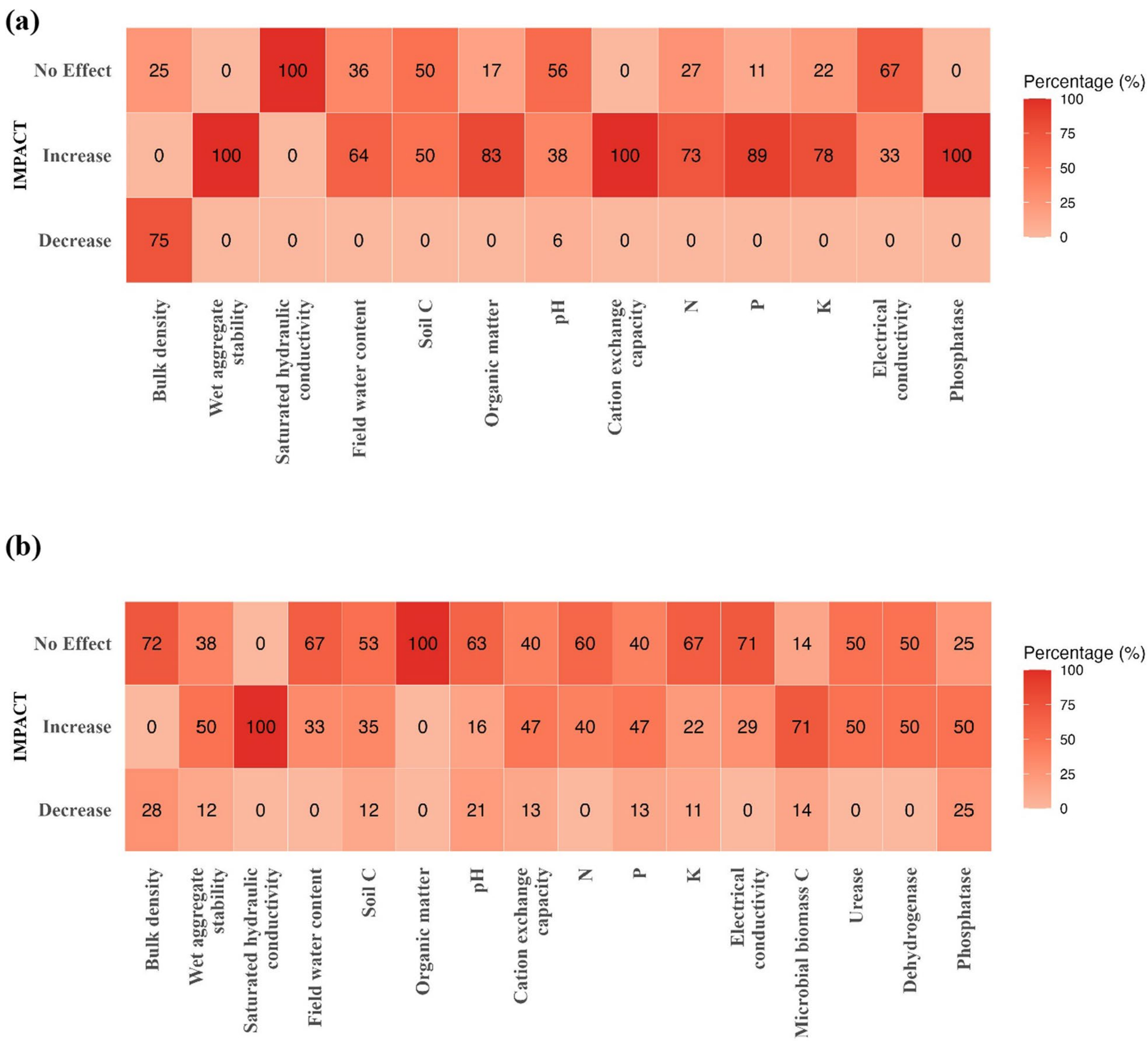


Fig. 4 Summary of the impacts of biochar co-application with amendments on soil properties, comparing **a** biochar combined with organic amendments and **b** biochar combined with inorganic amendments. Each column represents a soil property, while rows indicate the percentage of cases categorized as Increase, Decrease, or No Effect. The color gradient highlights the relative magnitude of these impacts

of 35), increased it in 26% (9 of 35), and decreased it in 14% (Fig. 3). In comparisons where changes occurred, soil pH increased by an average of 12% (6.1 vs. 6.7 units) or decreased by 3% (7.0 vs. 6.8 units) (Table 1; Table S6). These results suggest that mixing biochar with other amendments does not necessarily alter soil pH in most situations.

The reduction or lack of response in soil pH following biochar co-application could be due to various factors including amendment type and initial soil pH. Inorganic amendments such as N fertilizers have acidic effects, which likely explains the 14% of cases where soil pH decreased under biochar co-application (Sarma et al. 2018). Notably, most studies (28 of 35 comparisons) were conducted in soils with low initial pH (≤6.5). The observed increase in pH (0.6 units) in 26% of comparisons was primarily in these acidic soils, suggesting that biochar co-application is more effective at raising pH in low pH soils. This is in line with previous meta-analyses (Bai et al. 2022; Ye et al. 2020), which reported that biochar liming effect is more pronounced in acidic soils, likely due to increased base cation availability and organic acid neutralization.

The slight increase in pH observed in 26% of cases under biochar co-application may be due to the synergistic addition of alkaline materials and basic cations. For example, the addition of ash, alkaline substance from biochar, and the release of basic cations from microbial decarboxylation of organic amendments (manure and compost) could lead to an increase in soil pH (Agbede et al. 2019; Fischer and Glaser 2012; Yuan et al. 2011). However, biochar co-application did not consistently achieve a greater liming effect than biochar alone. Zhou et al. (2023) found no significant pH change with biochar-amended compost (a product from co-composting biochar with raw organic materials, rather than biochar and compost being applied separately to the soil), further supporting the idea that biochar interactions with organic amendments do not always enhance its liming effect.

The ability of biochar co-application to raise soil pH in acidic soils presents a potential strategy for improving soil conditions in regions with low pH, potentially reducing the need for lime applications. However, the lack of a consistent pH response indicates that biochar co-application alone may not be a reliable method for managing soil pH in all situations. In agricultural systems where soil pH is a critical factor, biochar co-application could be considered as part of a broader strategy that includes other amendments, such as lime or fertilizers, to optimize nutrient availability. Overall, existing literature suggests that biochar alone may provide a more consistent liming effect than biochar co-application, particularly in low-pH soils.

3.2.4 Cation exchange capacity

Cation exchange capacity is a critical soil property that determines the soil's ability to retain and supply nutrients essential for plant growth and nutrition (Ding et al. 2016). Our review identified seven studies (17 comparisons) assessing the effects of biochar co-application on CEC (Table 1). Biochar co-application increased CEC in 53% of comparisons (9 of 17), had no effect in 35% (6 of 17), and decreased it in 12% (Fig. 3). In cases where CEC increased, the improvement averaged 58% (7.9 vs. 10.2 cmol kg^{-1}) (Table 1), highlighting the potential of biochar co-application to enhance nutrient retention more effectively than biochar alone.

The observed increase in CEC (2.3 cmol kg^{-1}) with biochar co-application compared with biochar alone can be attributed to the joint effects of biochar and organic amendments. For instance, biochar contributes cations such as Ca^{2+}, Mg^{2+}, and K^{+}, while organic amendments like compost provide additional nutrients and increase charge density per unit surface area, thus enhancing the ability of soil to hold cations (Atkinson et al. 2010; Rajkovich et al. 2012; Zahra et al. 2021). In contrast, reductions in CEC (4.9 vs. 1.3 cmol kg^{-1}) or lack of effect in some cases under biochar co-application may result from a decrease in soil pH due to the acidic impact of inorganic amendments like N fertilizers. Notably, biochar co-application reduced pH (7.0 vs. 6.8 units) in 14% of comparisons (Fig. 3), thereby potentially limiting its ability to enhance CEC under these conditions.

The findings suggest that biochar co-application is a promising strategy for increasing CEC and improving nutrient retention in soils, especially when paired with organic amendments. Enhanced CEC contributes to optimum nutrient availability, reduced leaching losses, and improved soil fertility (Ding et al. 2016). These benefits may be more relevant for nutrient-depleted or sandy soils, where nutrient retention is often a limiting factor. However, the variability in responses shows the importance of considering soil conditions, amendment types, and pH interactions when designing biochar-based soil management strategies.

3.2.5 Nitrogen, phosphorus, and potassium

Nitrogen, P, and K are essential macronutrients required in large amounts for plant growth and crop productivity. Our review analyzed 16 studies (26 comparisons) on N, 14 studies (24 comparisons) on P, and 11 studies (18 comparisons) on K (Table 1). Biochar co-application increased N concentration in 54% of comparisons (14 of 26) and had no effect in the remaining 46% (Fig. 3). Also, biochar co-application increased P concentration in 63% of comparisons, had no effect in 29%, and decreased it in 8% (2 of 24). Similarly, biochar co-application increased K concentration in 50% of comparisons (9 of 18), had no effect in 44% (8 of 18) and decreased it in 6% (Fig. 3). Where increases occurred, concentrations rose by an average of 33% for N (1.1 vs. 1.5 g kg^{-1}), 76% for P (32.9 vs. 47.6 mg kg^{-1}), and 64% for K (108.4 vs. 144.1 mg kg^{-1}) (Table 1). These results suggest that biochar co-application can enhance soil N and P concentrations in most cases and K concentration in half of the cases relative to biochar alone.

The observed nutrient increases under biochar co-application are likely due to the high N, P, and K contents of many companion amendments. Organic amendments, such as manure and mineral fertilizers, typically contain significantly higher levels of N, P, and K than biochar derived from wood or crop residues (Jeffery et al. 2017). For example, manure nutrient concentrations can range from 10 to 29 g kg^{-1} for N, 2 to 14 g kg^{-1} for P, and 19 to 38 g kg^{-1} for K (Adekiya et al. 2020). Even biochars derived from nutrient-rich feedstocks like poultry litter or manure can supply significant amounts of nutrients

(Zahra et al. 2021). Thus, combining biochar with these nutrient-rich amendments improves overall nutrient input and soil fertility.

In addition to boosting nutrient supply, the co-application of biochar with amendments may influence nutrient dynamics through enhanced retention and transformation processes (Agegnehu et al. 2017; Zahra et al. 2021). The high surface area (up to 3000 m^2 g^{-1}) and CEC (2–37 cmol kg^{-1}) of biochar allow it to adsorb nutrients like ammonium, nitrate, and phosphate from the applied amendments, reducing their losses via leaching or volatilization (Adekiya et al. 2019; Blanco-Canqui 2017). Moreover, biochar co-application may affect N transformation processes such as mineralization, nitrification, and denitrification by modifying microbial activity, redox conditions, and sorption environments (Davys et al. 2023; Zhang et al. 2021). These interactions can enhance ammonium retention, reduce nitrate leaching, or mitigate nitrous oxide emissions, depending on the amendment type, soil properties, and environmental conditions. Thus, biochar co-application offers a promising approach to increasing soil nutrient concentrations, like N and P, and improving nutrient retention for sustainable agricultural production.

3.2.6 Electrical conductivity

Electrical conductivity can serve as an indicator of soil salinity, nutrient availability and loss, and water holding capacity (Corwin and Yemoto 2020). Our review summarized findings from 8 studies (10 comparisons) (Table 1; Fig. 3) assessing the effects of biochar co-application on soil EC. Biochar co-application had no effect on EC in 70% (7 of 10) of cases and increased it in the remaining 30% (3 of 10) (Fig. 3). In cases where EC increased, the average rise was 16% (0.33 vs. 0.39 dS m^{-1}) (Table 1). These results suggest that biochar co-application has minimal effects on soil EC.

The limited changes in EC in 70% of comparisons may be attributed to the type of amendments used. Most studies involved biochar co-application with inorganic fertilizers, such as NPK and Mg fertilizers (7 of 10 comparisons), which have limited effects on EC. In contrast, biochar co-application with compost accounted for one-third of the cases where EC increased, indicating the role of organic amendments in influencing soil EC (Table S9). Compost and manure typically contribute soluble salts and nutrients to the soil which can result in a modest increase in EC (USDA NRCS 2022).

Maintaining relatively stable EC levels under biochar co-application could be beneficial for salinity-sensitive cropping systems. The minimal impact on EC reduces the risk of salinity stress for plants, particularly in saline-prone soils or regions where water quality issues could exacerbate salinity problems. Indeed, high EC (>4 dS m^{-1}) not only impedes crop water uptake and microbial activity but also leads to poor soil structure, reduced drainage, and sodium toxicity, indicating the need for balanced soil management strategies (USDA NRCS 2022). The slight increase in EC observed under biochar co-application with compost compared to inorganic fertilizers suggests the importance of selecting amendments based on soil-specific requirements and crop tolerance. For example, in nutrient-depleted soils, a moderate increase in EC may boost nutrient availability, while in saline soils, maintaining low EC levels would be a priority.

3.3 Soil biological properties

Thriving soil microbial populations and activities are essential for enhancing soil health and ecosystem services (Adetunji et al. 2017; Lehmann et al. 2011). Microbial biomass, diversity, and enzyme activities play critical roles in nutrient cycling, organic matter decomposition, soil aggregation, and other dynamic soil processes. Therefore, management strategies that can boost biochar efficiency for enhancing soil biological properties are needed, particularly in areas susceptible to soil degradation.

Our review found 4 studies (7 comparisons) on microbial biomass C, 2 studies (4 comparisons) on urease, 2 studies (4 comparisons) on dehydrogenase, and 3 studies (5 comparisons) on phosphatase (Table 1). Biochar co-application increased microbial biomass C in 71% of comparisons (5 of 7), had no effect in 14%, and decreased it in 14% (Fig. 5). For phosphatase, biochar co-application increased activities in 60% of comparisons, decreased it in 20%, and had no effect in 20% (Fig. 5). Further, biochar co-application increased urease and dehydrogenase activities in 50% of comparisons and had no effect in the other 50% (2 of 4).

The limited data indicate that biochar co-application increased soil biomass C (201 vs 253 mg kg^{-1}) and phosphatase activities (29 vs. 62 μg PNP g^{-1} h^{-1}) more effectively than biochar alone. However, urease activities (6 vs. 7 μmol $NH4^{+}$ g^{-1} h^{-1}) and dehydrogenase activities (27 vs. 32 mg TPF g^{-1} h^{-1}) improved in only half of the cases, reflecting inconsistent responses. Biochar co-application probably enhanced some soil biological properties via various mechanisms. First, biochar's large pore surface area (up to 3000 m^2 g^{-1}) compared to agricultural soils (10–250 m^2 g^{-1}) provides favorable microhabitats for microbial communities by retaining C substrates and mineral nutrients from added amendments (Azeem et al. 2019). Second, the synergistic effects of biochar and organic amendments (e.g., compost) can increase substrate quality and nutrient availability, thereby promoting microbial growth and enzyme activities (Cao et al. 2017;

Fig. 5 Summary of biochar co-application impacts on soil biological properties compared to biochar alone. Each column represents a soil biological property, while the rows indicate the percentage of impacts categorized as Increase, Decrease, or No Effect. The color gradient highlights the relative magnitude of these impacts

Irfan et al. 2019). These enhancements are particularly important as dehydrogenase and urease activities are closely tied to N cycling, while phosphatase activities are associated with phosphorus cycling, both of which are vital for soil fertility. However, the variability in urease and dehydrogenase responses suggest that biochar co-application effects may depend on soil type, amendment composition, and application rates.

4 Potential factors that may influence biochar co-application benefits

Understanding the factors that influence the effectiveness of biochar co-application on soil properties is essential for optimizing its benefits and guiding context-specific soil management practices. These factors, illustrated in Fig. 6, include application rates, amendment types, biochar characteristics, soil properties, and environmental or agronomic conditions. Importantly, soil is inherently a heterogeneous porous medium, with spatial variability in texture, structure, mineralogy, and organic matter distribution (Lehmann et al. 2020). This heterogeneity can influence water flow, amendment retention, nutrient cycling, and microbial responses, thereby moderating how soils respond to the co-application of biochar and amendments. Some of the key factors that may influence the soil response to biochar co-application are discussed below.

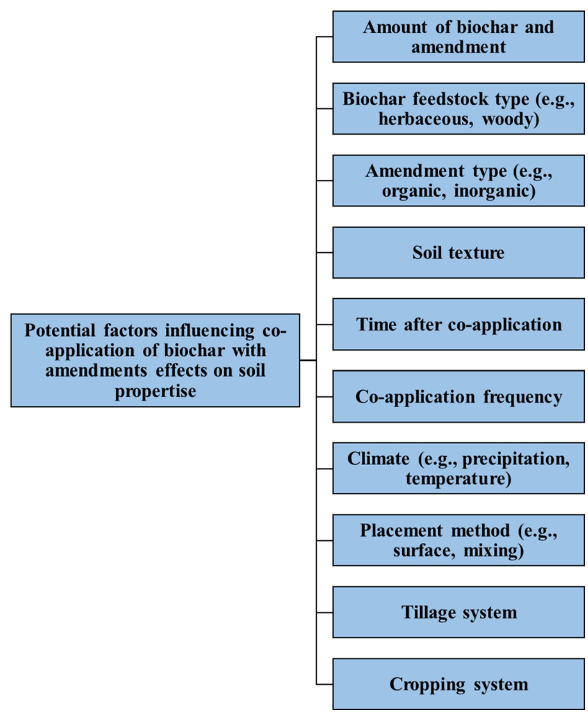


Fig. 6 Potential factors influencing the performance of biochar co-application with other amendments on soil properties

4.1 Biochar and amendment application rate

Synthesis of data showed that the rate of biochar co-application can influence soil benefits of biochar co-application (Tables S1–S10). For example, an increase in biochar co-application amount increased the effectiveness of the co-application to reduce soil bulk density by 7% and increase wet aggregate stability by 3%, saturated hydraulic conductivity by 16%, and field water content by 15% (Fig. 7). An increase in biochar co-application rate also increased concentrations of C by 16%, organic matter by 15%, N by 14%, P by 40%, K by 37%, and CEC by 11%, and microbial biomass C by

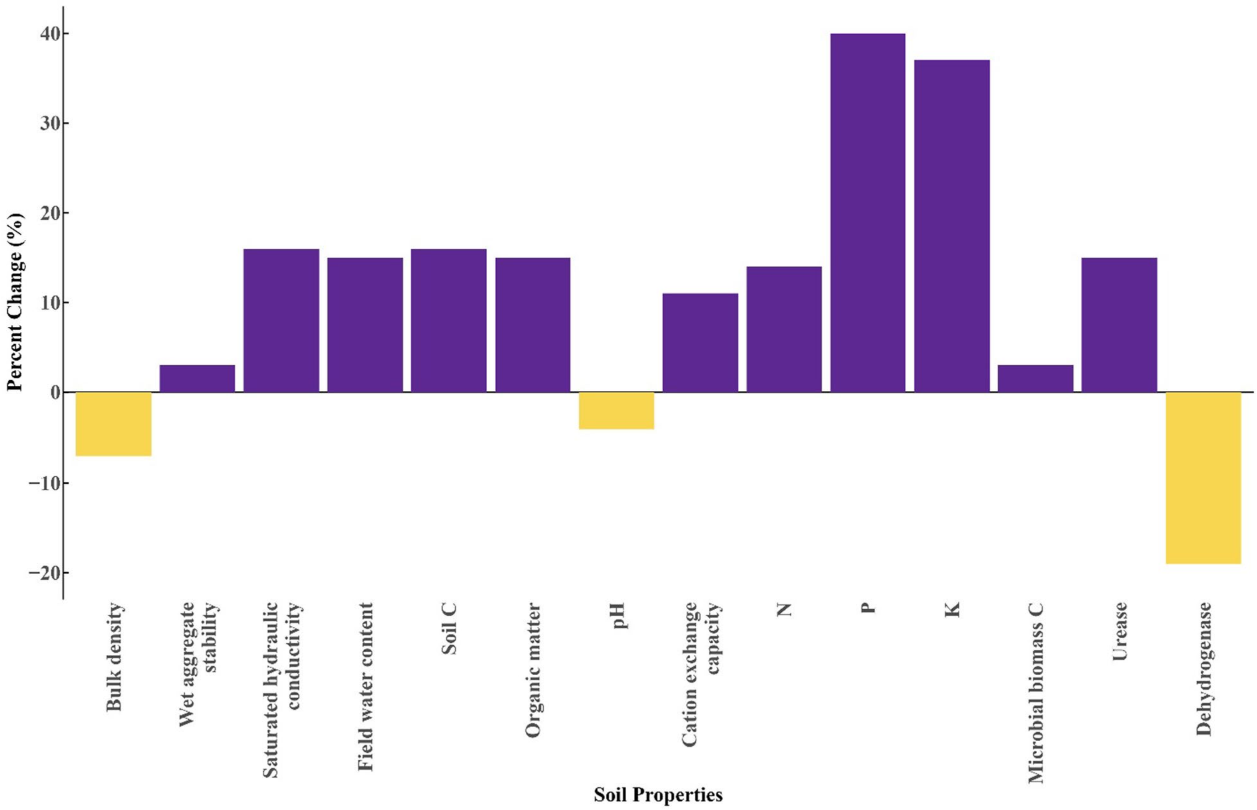


Fig. 7 Percent change in soil properties in response to increased biochar co-application rates. Positive values indicate an increase in the measured property, while negative values indicate a decrease

3%, and urease activities by 15% (Fig. 7). However, an increase in biochar co-application amount can decrease the potential of co-application to increase soil pH (4%) and dehydrogenase activities (19%) (Fig. 7). How EC and soil biological properties respond to different biochar co-application rates is still unclear because the few studies on these soil properties used only one rate of biochar co-application.

It is important to determine the minimum rate of biochar and amendment needed to improve soil properties for economic feasibility and large-scale use of biochar and amendments. The minimum rate can depend on the amendment type. Based on our review (Tables S1–S10), at least 25 Mg ha^{-1} of biochar combined with 5 Mg ha^{-1} of compost or manure may be needed to improve soil physical and chemical properties, while at least 5 Mg ha^{-1} of biochar with about 200 kg ha^{-1} inorganic amendments may be required to enhance soil physical and chemical properties. However, the minimum co-application rate that can benefit soil biological properties is still unknown due to limited data. More studies testing multiple co-application rates are needed to establish the minimum levels of co-application rates.

4.2 Amendment type

Tables S1–S10 show that most comparisons were from biochar co-application with inorganic amendments (62%) relative to biochar co-application with organic amendments (38%). Biochar co-application with organic amendments improved bulk density, C, pH, N, P, and K more than inorganic amendments. For instance, biochar co-application with organic amendments (Fig. 4a; Appendix) reduced soil bulk density in 75% of comparisons (9 of 12), and increased C in 50% of comparisons (5 of 10) and pH in 38% of comparisons (6 of 16), relative to co-application with inorganic amendments (Fig. 4b; Appendix). Biochar co-application with organic amendments also increased soil N in 73% of comparisons (8 of 11), P in 89% of comparisons (8 of 9), and K in 78% of comparisons (7 of 9), compared to co-application with inorganic amendments. Effects of amendment type on the remaining soil properties, including biological indicators, remain unclear due to limited data. However, biochar co-application with organic amendments consistently improved soil physicochemical properties more than with inorganic amendments, likely due to better soil structure and nutrient contributions from organic matter. Co-application with

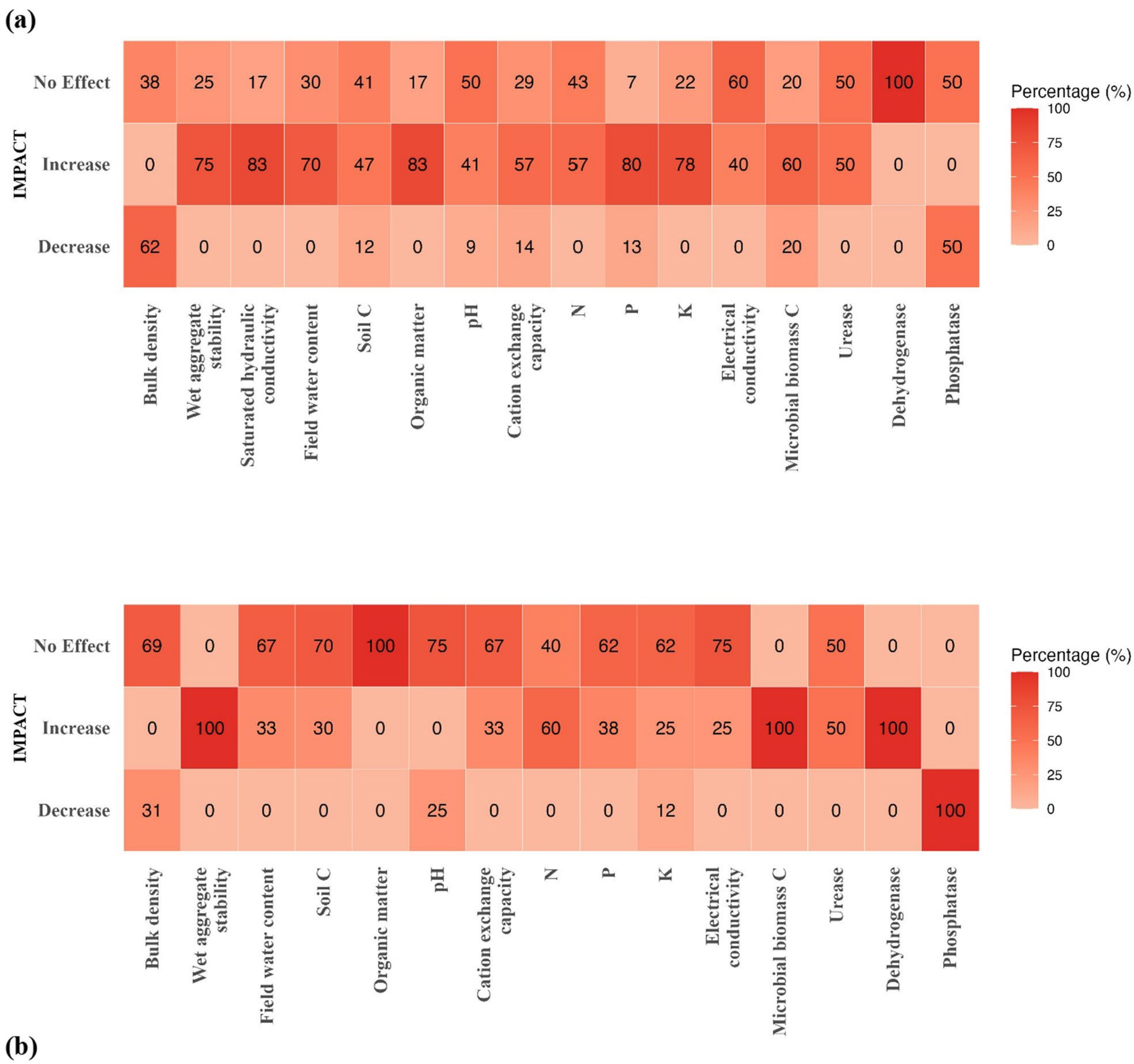


Fig. 8 Summary of the impacts of biochar co-application with amendments on soil properties, comparing **a** low initial soil C (≤10.5 g kg^{-1}) and **b** high initial soil C (≥10.6 g kg^{-1}). Each column represents a soil property, while rows indicate the percentage of cases categorized as Increase, Decrease, or No Effect. The color gradient highlights the relative magnitude of these impacts

compost has shown synergistic effects on nutrient availability, microbial activity, and soil structure, warranting amendment-specific investigations (Agegnehu et al. 2017; Liu et al. 2016; Schmidt et al. 2021).

4.3 Initial soil C concentration

Initial soil C concentration in the reviewed studies ranged from 3.6 to 32.5 g kg^{-1} (0.36% to 3.25% C). Table S11 shows that 64% of comparisons were from studies conducted in low C soils (≤10.5 g kg^{-1}). Soils with low initial C (≤10.5 g kg^{-1}) (Fig. 8a; Appendix) enhanced the ability of biochar co-application to reduce bulk density in 62% of comparisons and increase pH in 41%, as well as N, P, and K concentrations in 57%, 80%, and 78% of cases, respectively, compared to soils with high initial C (≥10.6 g kg^{-1}) (Fig. 8b; Appendix). In contrast, biochar co-application increased soil dehydrogenase activity more in high C soils than in low C soils. Initial soil C concentration did not affect co-application benefits for soil microbial biomass C, and urease and phosphatase activities. How initial soil C influences biochar co-application effects on the remaining soil properties is still unclear as most studies

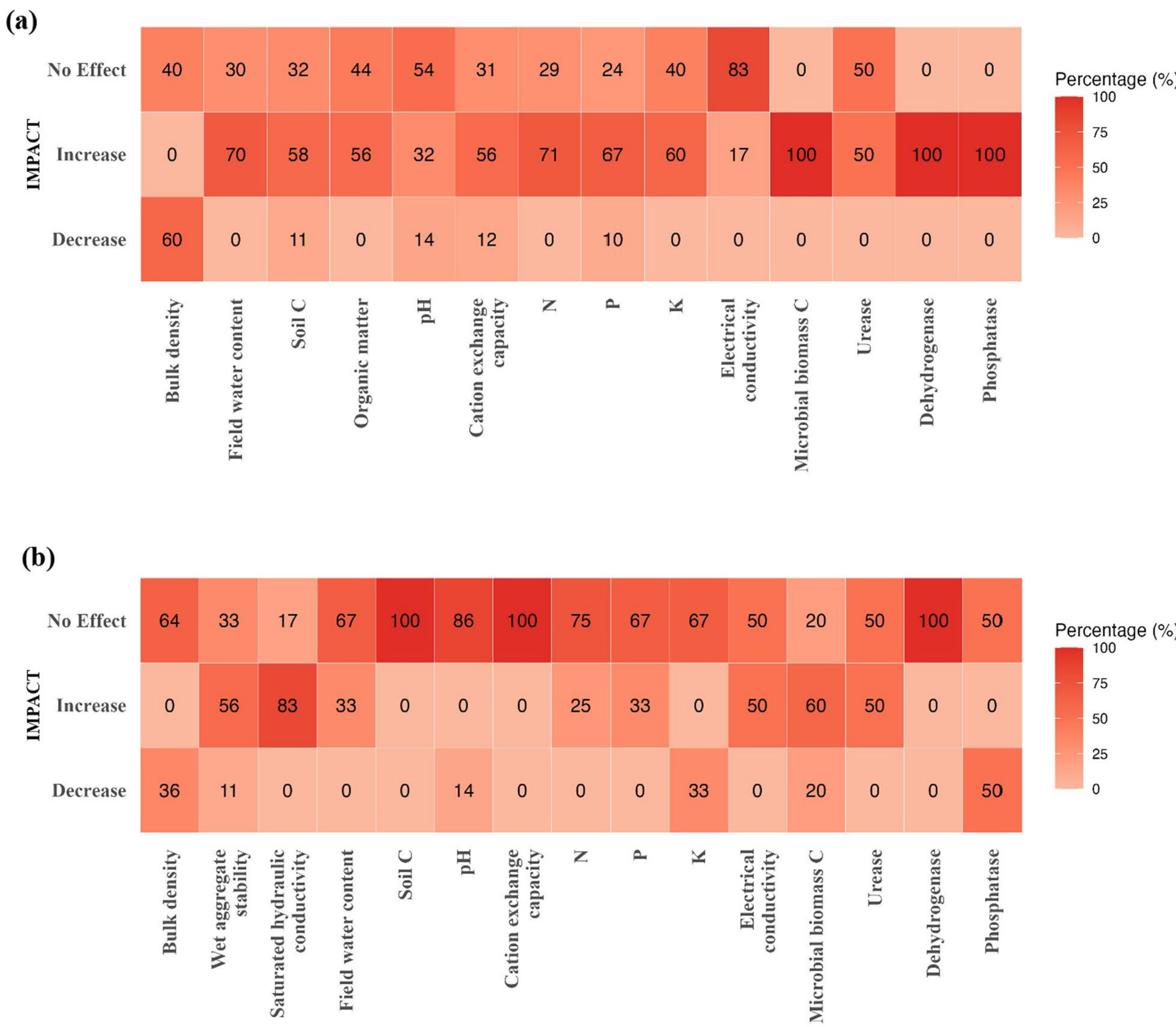


Fig. 9 Summary of the impacts of biochar co-application with amendments on soil properties, comparing **a** low initial soil pH (≤6.5) and (**b** high initial soil pH (≥6.6). Each column represents a soil property, while rows indicate the percentage of cases categorized as Increase, Decrease, or No Effect. The color gradient highlights the relative magnitude of these impacts

were from soils with low initial C concentrations. Previous reviews have shown that soils with lower initial C may respond quicker to biochar applications than those with high initial C (Ibrahimi and Alghamdi 2022). This is because less fertile soils have lower C saturation levels and more room for C increase compared to C-rich or fertile soils (Blanco-Canqui 2021). Data available suggest that biochar co-application tends to increase the effectiveness of biochar to enhance some soil properties (bulk density, pH, and N, P, and K concentrations) in low C soils compared to high C soils.

4.4 Initial soil pH

Table S12 shows that 68% of comparisons were from studies conducted in soils with low initial pH (initial soil pH ≤ 6.5). Biochar co-application reduced soil bulk density and increased C and N concentrations, as well as dehydrogenase and phosphatase activities, more effectively in low pH soils than in high pH soils (pH ≥ 6.6) (Fig. 9, Appendix; Table S12). However, high pH soils increased biochar co-application effectiveness to increase soil EC compared to low pH soils. Initial soil pH did not affect biochar co-application benefits for microbial biomass C and urease activities.

These findings suggest that biochar co-application may be more effective at improving soil physical and biological properties in acidic soils, while high pH soils may be more responsive in terms of EC. However, how initial soil pH affects biochar co-application effects on wet aggregate stability, saturated hydraulic conductivity, field water content, organic matter, CEC, P, and K is still unclear due to the limited number of studies conducted in high pH soils. Previous reviews have also noted the scarcity of data on how soil pH modulates the broader impacts of biochar on these properties (Blanco-Canqui 2017; Bai et al. 2022). In sum, biochar co-application can reduce soil bulk density and increase C, N, and dehydrogenase and phosphatase activities in low pH soils, while it can increase soil EC in high pH soils.

4.5 Soil texture

Table S13 indicates that most of the published studies were conducted on coarse-textured soils. Seventy one percent of comparisons were from studies on coarse-textured soils, 20% on medium-textured soils, and 9% on fine-textured soils. Thus, a valid comparison of how soil texture affects soil properties under biochar co-application is not possible as most studies were from coarse-textured soils.

However, how soil textural classes affect the impacts of biochar alone on soil properties has been widely reported. Reports from meta-analysis (Jeffery et al. 2011; Schmidt et al. 2021; Singh et al. 2022) and reviews (Blanco-Canqui 2017; Omondi et al. 2016) show that sole biochar application can improve soil properties in coarse-textured soils more than in medium- and fine-textured soils. Coarse-textured soils often have high bulk density, low C concentrations, and low water and nutrient retention capacity compared with medium- and fine-textured soils. Because application of biochar alone benefits soil properties more in coarse-textured soils than in fine-textured soils, we expect that biochar co-application benefits on soil properties would also be greater in coarse-textured soils than in fine-textured soils.

5 Implications of combined biochar and amendment-induced changes in soil properties on crop production

Our systematic analysis reveals that co-application of biochar with other amendments can improve soil properties such as wet aggregate stability, saturated hydraulic conductivity, field water content, organic matter, CEC, N, P, biomass C, and phosphatase activities more than biochar alone. Improvement of these soil properties could eventually result in improved crop yield.

Previous reviews have associated increase in crop yield following biochar co-application with improvement in soil properties (Bai et al. 2022; Ye et al. 2020). The reviews (Bai et al. 2022; Ye et al. 2020) reported highest increase in crop yield in low pH soils and attributed such benefit to the short-term liming effect of biochar, and nutrient inputs by biochar and fertilizer. A number of individual biochar co-application studies have also attributed increase in crop yields such as radish tuber (Adekiya et al. 2019), wheat grain (Ibrahim et al. 2019), tea plant (Yang et al. 2021), and watermelon (Cao et al. 2017) yields to reduced bulk density and increased aggregate stability, organic matter, and nutrient availability, and enhanced microbial biomass and activity of soils.

Just as meta-analyses (Bai et al. 2022; Ye et al. 2020) reported the highest crop yield increase in low pH soils after biochar co-application, our review also found that biochar co-application increases pH more than biochar alone in low pH soils ($pH \leq 6.5$). This thus affirms the capacity of biochar co-application to increase crop yield in low pH soils (Bai et al. 2022; Ye et al. 2020). Soil pH influences microbial N mineralization which affects availability of N to plants (Nguyen et al. 2018). Also, in low pH soils, increase in soil pH after co-application of biochar with amendments can reduce aluminum toxicity levels and aid P availability for crop uptake (Ye et al. 2020). In general, co-application of biochar with other amendments can enhance soil properties, which could ultimately increase crop productivity.

6 Research needs

1. Most of the studies available are from laboratory and greenhouse experiments. More comprehensive field studies in different soil types, management practices, and climates are needed to: (1) fully understand the impacts of biochar and amendment combinations on soil properties and (2) make firm recommendations for large-scale application of biochar and amendment combinations.
2. Current studies are predominantly short-term (<3 years). Long-term field studies are essential to capture the delayed synergistic effects of biochar and amendment interactions, particularly on soil physical properties like wet and dry aggregate stability, water infiltration, and hydraulic conductivity. These properties often change slowly, and their response to biochar co-application requires extended observation.
3. Data available show that an increase in biochar co-application rate can improve most soil properties. Yet, the ideal application amount for biochar and amendment combination for the improvement of soil properties has not been established. Long-term field studies are needed to establish minimum

or appropriate amount of combination (i.e., ratio) to ensure efficient use of resources and provide practical recommendations for different soil types, amendment types, and climates.

4. Most field studies focused on sandy loam soils, leaving a gap in understanding biochar co-application effects in medium- and fine-textured soils. Medium- and fine-textured soils have different physical and chemical characteristics, such as higher water holding capacity, greater nutrient availability, and differing microbial dynamics, which can influence biochar co-application efficacy. Addressing this gap is essential to optimize biochar benefits across a wider range of soil textures.
5. Studies indicated that biochar application can have more positive effects in degraded soils than in highly fertile soils (El-Naggar et al. 2019). However, how biochar co-application performs in such contrasting soil conditions is unclear as most biochar co-application studies were conducted in relatively fertile soils. The limited data on EC from our review further highlights these differences. Findings on EC indicate that biochar co-application has minimal effects on EC in 70% of cases, with moderate increases observed in 30%, primarily when organic amendments like compost are used. This suggests that in degraded soils, where nutrient availability is often limited, even a modest increase in EC could signify enhanced nutrient retention and availability, thus benefiting soil fertility and crop productivity. Conversely, in fertile or saline soils, maintaining low EC levels is crucial to avoid salinity related issues such as poor drainage, sodium toxicity, and reduced microbial activity. Indeed, degraded soils can benefit significantly from biochar co-application by improving nutrient retention, soil structure, and microbial activity, whereas fertile soils may require less intervention. Future research should prioritize long-term studies to evaluate biochar co-application effects on soil properties across diverse fertility levels. This will enable the development of precise guidelines for maximizing biochar co-application potential in restoring degraded soils while maintaining balance in fertile and saline-prone systems.
6. Most studies focused on the combination of biochar with organic amendments such as compost and manure, and not with other important amendments. Research is needed to evaluate the potential synergistic effect of biochar when combined with green manure, crop residues, cover crops, biosolids, degradable mulches, and other amendments. Understanding these interactions can lead to more effective and diverse soil management strategies. Indeed, co-application of biochar with other organic amendments will provide information on the ideal organic amendments to mix with biochar for optimum benefits depending on soil situation and biochar co-application goals.
7. Studies mostly measured soil bulk density, water content, pH, and nutrient concentrations (Table 1). Data on other important properties such as wet and dry aggregate stability, saturated hydraulic conductivity, plant available water, water infiltration, soil organic matter, microbial diversity, bacterial and fungi growth, and fauna population (nematodes and earthworms) are sparse. Expanding the scope of measured properties will provide a holistic understanding of biochar co-application impact on soil health.
8. Most experiments assess the effects of a one-time biochar co-application. A need exists to determine how soil properties respond to annual or split application of biochar combined with other amendments to maintain co-application benefits. This is necessary to understand how repeated or distributed biochar co-applications influence long-term soil health, nutrient dynamics, and crop productivity. Such research can provide insights into the sustainability and cumulative benefits or potential drawbacks of biochar co-application over time, providing more effective and lasting soil management practices.
9. Studies examining the influence of methods of biochar co-application on soil properties are lacking. Application of biochar and amendments to the whole field increases the combination amount and application costs. Co-application of biochar and amendments closer to crops across the field can save material amount and cost, and allow biochar and amendments-soil-root contact for better efficiency. Thus, field research evaluating the impact and feasibility of banding or placing biochar and amendment mixture in crop rows across the whole field is needed. Similarly, the optimum depth of biochar and amendment incorporation into the soil to achieve maximum benefits has not been well defined. The depth of incorporation could affect the extent to which biochar and amendments interact with soil particles and create changes in soil properties. The depth of incorporation could also affect the retention time of biochar and amendments in the soil and influence plant root uptake of nutrients supplied through co-application.

10. The economics of biochar co-application with other amendments have not been widely addressed (Danso et al. 2023). The co-application of biochar with other amendments increases the total amount of material applied. Also, frequent co-applications may be needed to sustain soil health and crop productivity in degraded or low fertility soils which can increase costs. Further, mixing or co-applying biochar with other amendments is a hassle or more work relative to applying biochar alone. Thus, the initial investment in biochar and other amendments and the labor and resources required for co-application could be significant (Chen et al. 2022), necessitating a careful cost–benefit analysis. Such studies will determine the economic implications and cost benefits of biochar co-application for decision-making processes.

7 Conclusion

Our review suggests that compared to biochar alone, biochar applied with other amendments can improve certain soil physical (wet aggregate stability, saturated hydraulic conductivity, and field water content), chemical (CEC, and organic matter, N, and P concentrations), and microbial properties (biomass C and phosphatase activities). However, it may not consistently improve soil bulk density, pH, EC, C and K concentrations, and urease and dehydrogenase activities. The benefits of biochar co-application tend to increase with higher application rates, particularly when combined with organic (compost/manure) rather than inorganic (NPK) amendments. Soil type and initial conditions influence biochar co-application effects. It is particularly beneficial in low pH soils (≤6.5), where it improves bulk density, nutrient availability, and enzyme activity, whereas in high pH soils (≥6.6), it may increase EC, requiring careful amendment selection. Similarly, greater benefits are observed in coarse-textured soils but studies on medium and fine-textured soils remain limited.

Current studies lack comprehensive assessments of all soil health indicators, such as microbial diversity, water infiltration, water retention, and interactions between amendment types, biochar application methods, and soil properties. Furthermore, the long-term effects of biochar co-application under varying soils, climates, and amendment regimes remain poorly understood. In summary, while biochar co-application shows potential for enhancing soil health, more comprehensive, long-term (>5 years) field studies are required to optimize its use and fully realize its benefits. Future research should adopt an approach that explicitly traces how biochar co-application practices affect specific soil responses and translate into agronomic or ecological outcomes. Such a cause-evidence-impact perspective can clarify biochar co-application outcomes and guide more targeted, sustainable soil management strategies for climate change mitigation and global food security.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s42773-025-00531-6.

Additional file 1.

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Data availability
Data will be made available on request.

Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Adekiya A, Agbede T, Aboyeji C, Dunsin O, Simeon V (2019) Biochar and poultry manure effects on soil properties and radish (*Raphanus sativus* L.) yield. Biol Agric Hortic 35:33–45
Adekiya AO, Olaniran AF, Adenusi TT, Aremu C, Ejue WS, Iranloye YM, Gbadamosi A, Olayanju A (2020) Effects of cow dung and wood biochars and green manure on soil fertility and tiger nut (*Cyperus esculentus* L.) performance on a savanna Alfisol. Sci Rep 10:21021
Adetunji AT, Lewu FB, Mulidzi R, Ncube B (2017) The biological activities of β-glucosidase, phosphatase and urease as soil quality indicators: a review. J Soil Sci Plant Nutr 17:794–807
Agbede TM, Adekiya AO, Ale MO, Eifediyi EK, Olatunji CA (2019) Effects of green manures and NPK fertilizer on soil properties, tomato yield and quality in the forest-savanna ecology of Nigeria. Exp Agric 55:793–806
Agegnehu G, Srivastava AK, Bird MI (2017) The role of biochar and biochar-compost in improving soil quality and crop performance: a review. Appl Soil Ecol 119:156–170
Atkinson CJ, Fitzgerald JD, Hipps NA (2010) Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant Soil 337:1–18
Ayaz M, Feizienė D, Feiza V, Tilvikienė V, Baltrėnaitė-Gedienė E, Khan A (2022) The impact of swine manure biochar on the physical properties and microbial activity of loamy soils. Plants 11:1729
Azeem M, Hayat R, Hussain Q, Ahmed M, Pan G, Tahir MI, Imran M, Irfan M (2019) Biochar improves soil quality and N2-fixation and reduces net

ecosystem CO2 exchange in a dryland legume-cereal cropping system. Soil till Res 186:172–182
Bai SH, Omidvar N, Gallart M, Kämper W, Tahmasbian I, Farrar MB, Singh K, Zhou G, Muqadass B, Xu C-Y (2022) Combined effects of biochar and fertilizer applications on yield: a review and meta-analysis. Sci Total Environ 808:152073
Balaganesh P, Vasudevan M, Natarajan N (2022) Evaluating sewage sludge contribution during co-composting using cause-evidence-impact analysis based on morphological characterization. Environ Sci Pollut Res 29:51161–51182
Biederman LA, Harpole WS (2013) Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. GCB Bioenergy 5:202–214
Blanco-Canqui H (2017) Biochar and soil physical properties. Soil Sci Soc Am J 81:687–711
Blanco-Canqui H (2021) Does biochar improve all soil ecosystem services? GCB Bioenergy 13:291–304
Borenstein M, Hedges LV, Higgins JP, Rothstein HR (2021) Introduction to meta-analysis. John Wiley & Sons
Bot A, Benites J (2005) The importance of soil organic matter: key to drought-resistant soil and sustained food production. Food & Agriculture Org.
Cao Y, Ma Y, Guo D, Wang Q, Wang G (2017) Chemical properties and microbial responses to biochar and compost amendments in the soil under continuous watermelon cropping. Plant Soil Environ 63:1–7
Celestina C, Hunt JR, Sale PW, Franks AE (2019) Attribution of crop yield responses to application of organic amendments: a critical review. Soil Tillage Res 186:135–145
Chen L, Li X, Peng Y, Xiang P, Zhou Y, Yao B, Zhou Y, Sun C (2022) Co-application of biochar and organic fertilizer promotes the yield and quality of red pitaya (*Hylocereus polyrhizus*) by improving soil properties. Chemosphere 294:133619
Corwin DL, Yemoto K (2020) Salinity: Electrical conductivity and total dissolved solids. Soil Sci Soc Am J 84:1442–1461
Danso F, Agyare WA, Bart-Plange A (2023) Benefits and costs of cultivating rice using biochar-inorganic fertilizer combinations. J Agric Food Res 11:100491
Davys D, Rayns F, Charlesworth S, Lillywhite R (2023) The effect of different biochar characteristics on soil nitrogen transformation processes: a review. Sustainability 15:16446
Ding Y, Liu Y, Liu S, Li Z, Tan X, Huang X, Zeng G, Zhou L, Zheng B (2016) Biochar to improve soil fertility. A review. Agron Sustain Dev 36:1–18
Ding F, Van Zwieten L, Zhang W, Weng Z, Shi S, Wang J, Meng J (2018) A meta-analysis and critical evaluation of influencing factors on soil carbon priming following biochar amendment. J Soils Sed 18:1507–1517
El-Naggar A, Lee SS, Rinklebe J, Farooq M, Song H, Sarmah AK, Zimmerman AR, Ahmad M, Shaheen SM, Ok YS (2019) Biochar application to low fertility soils: a review of current status, and future prospects. Geoderma 337:536–554
Fierer N, Wood SA, De Mesquita CPB (2021) How microbes can, and cannot, be used to assess soil health. Soil Biol Biochem 153:108111
Fischer D, Glaser B (2012) Synergisms between compost and biochar for sustainable soil amelioration. In Kumar S, Bharti A (eds) Management of organic waste. Janeza Trdine 9, 51000 Rijeka, Croatia: InTech
Haydu-Houdeshell C-A, Graham RC, Hendrix PF, Peterson AC (2018) Soil aggregate stability under chaparral species in southern California. Geoderma 310:201–208
He M, Xiong X, Wang L, Hou D, Bolan NS, Ok YS, Rinklebe J, Tsang DC (2021) A critical review on performance indicators for evaluating soil biota and soil health of biochar-amended soils. J Hazard Mater 414:125378
Ibrahim M, Mahmoud E, Gad L, Khader A (2019) Effects of biochar and phosphorus fertilizer rates on soil physical properties and wheat yield on clay textured soil in middle Nile Delta of Egypt. Commun Soil Sci Plant Anal 50:2756–2766
Ibrahimi K, Alghamdi AG (2022) Available water capacity of sandy soils as affected by biochar application: a meta-analysis. CATENA 214:106281
Irfan M, Hussain Q, Khan KS, Akmal M, Ijaz SS, Hayat R, Khalid A, Azeem M, Rashid M (2019) Response of soil microbial biomass and enzymatic activity to biochar amendment in the organic carbon deficient arid soil: a 2-year field study. Arab J Geosci 12:1–9
Jeffery S, Verheijen FG, Van Der Velde M, Bastos AC (2011) A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric Ecosyst Environ 144:175–187
Jeffery S, Abalos D, Prodana M, Bastos AC, Van Groenigen JW, Hungate BA, Verheijen F (2017) Biochar boosts tropical but not temperate crop yields. Environ Res Lett 12:053001
Kang S-W, Kim S-H, Park J-H, Seo D-C, Ok YS, Cho J-S (2018) Effect of biochar derived from barley straw on soil physicochemical properties, crop growth, and nitrous oxide emission in an upland field in South Korea. Environ Sci Pollut R 25:25813–25821
Khademalrasoul A, Naveed M, Heckrath G, Kumari K, De Jonge LW, Elsgaard L, Vogel H-J, Iversen BV (2014) Biochar effects on soil aggregate properties under no-till maize. Soil Sci 179:273–283
Khater E-SG (2015) Some physical and chemical properties of compost. Int J Waste Resour 5:72–79
Laird D, Fleming P, Wang B, Horton R, Karlen D (2010) Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma 158:436–442
Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D (2011) Biochar effects on soil biota–a review. Soil Biol Biochem 43:1812–1836
Lehmann J, Bossio DA, Kögel-Knabner I, Rillig MC (2020) The concept and future prospects of soil health. Nat Rev Earth Environ 1:544–553
Liu S, Zhang Y, Zong Y, Hu Z, Wu S, Zhou J, Jin Y, Zou J (2016) Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: a meta-analysis. Gcb Bioenergy 8:392–406
Manea EE, Bumbac C, Dinu LR, Bumbac M, Nicolescu CM (2024) Composting as a sustainable solution for organic solid waste management: current practices and potential improvements. Sustainability 16:6329
Naeem MA, Khalid M, Aon M, Abbas G, Amjad M, Murtaza B, Khan W-U-D, Ahmad N (2018) Combined application of biochar with compost and fertilizer improves soil properties and grain yield of maize. J Plant Nutr 41:112–122
Nguyen TTN, Wallace HM, Xu C-Y, Zwieten LV, Weng ZH, Xu Z, Che R, Tahmasbian I, Hu H-W, Bai SH (2018) The effects of short term, long term and reapplication of biochar on soil bacteria. Sci Total Environ 636:142–151
Omondi MO, Xia X, Nahayo A, Liu X, Korai PK, Pan G (2016) Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. Geoderma 274:28–34
Pop E, Mihăescu L, Lăzăroiu G, Pîşă I, Negreanu G, Berbece V (2019) Energy characteristics of the char obtained by two steps pyrolysis of chicken manure. IOP Conference Series: Materials Science and Engineering. IOP Publishing, 012051
Premalatha RP, Poorna Bindu J, Nivetha E, Malarvizhi P, Manorama K, Parameswari E, Davamani V (2023) A review on biochar's effect on soil properties and crop growth. Front Energy Res 11:1092637
Qi S, Degen A, Wang W, Huang M, Li D, Luo B, Xu J, Dang Z, Guo R, Shang Z (2024) Systemic review for the use of biochar to mitigate soil degradation. GCB Bioenergy 16:e13147
Qian S, Zhou X, Fu Y, Song B, Yan H, Chen Z, Sun Q, Ye H, Qin L, Lai C (2023) Biochar-compost as a new option for soil improvement: application in various problem soils. Sci Total Environ 870:162024
Rajapaksha AU, Chen SS, Tsang DC, Zhang M, Vithanage M, Mandal S, Gao B, Bolan NS, Ok YS (2016) Engineered/designer biochar for contaminant removal/immobilization from soil and water: potential and implication of biochar modification. Chemosphere 148:276–291
Rajkovich S, Enders A, Hanley K, Hyland C, Zimmerman AR, Lehmann J (2012) Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. Biol Fertility Soils 48:271–284
Rohatgi AW (2021) https://automeris.io/. WebPlotDigitizer. Accessed 22 Oct 2018
Sarma B, Gogoi N, Bharali M, Mali P (2018) Field evaluation of soil and wheat responses to combined application of hardwood biochar and inorganic fertilizers in acidic sandy loam soil. Exp Agric 54:507–519
Schmidt HP, Kammann C, Hagemann N, Leifeld J, Bucheli TD, Sánchez Monedero MA, Cayuela ML (2021) Biochar in agriculture–a systematic review of 26 global meta-analyses. GCB Bioenergy 13:1708–1730
Singh H, Northup BK, Rice CW, Prasad PV (2022) Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. Biochar 4:8
Somerville PD, Farrell C, May PB, Livesley SJ (2020) Biochar and compost equally improve urban soil physical and biological properties and tree growth, with no added benefit in combination. Sci Total Environ 706:135736

Trivedi P, Singh BP, Singh BK (2018) Soil carbon: introduction, importance, status, threat, and mitigation. In: Singh BK (ed) Soil carbon storage. Elsevier, Amsterdam
USDA Natural Resources Conservation Service (2022) Soil quality indicators: soil electrical conductivity. Soil Quality Physical Indicator Information Sheet Series
Usowicz B, Lipiec J (2021) Spatial variability of saturated hydraulic conductivity and its links with other soil properties at the regional scale. Sci Rep 11:8293
Wang L, Deng J, Yang X, Hou R, Hou D (2023) Role of biochar toward carbon neutrality. Carbon Res 2:2
Yang W, Li C, Wang S, Zhou B, Mao Y, Rensing C, Xing S (2021) Influence of biochar and biochar-based fertilizer on yield, quality of tea and microbial community in an acid tea orchard soil. Appl Soil Ecol 166:104005
Ye L, Camps-Arbestain M, Shen Q, Lehmann J, Singh B, Sabir M (2020) Biochar effects on crop yields with and without fertilizer: a meta-analysis of field studies using separate controls. Soil Use Manage 36:2–18
Yuan J-H, Xu R-K, Zhang H (2011) The forms of alkalis in the biochar produced from crop residues at different temperatures. Bioresour Technol 102:3488–3497
Zahra MB, Fayyaz B, Aftab Z-E, Haider MS (2021) Mitigation of degraded soils by using biochar and compost: a systematic review. J Soil Sci Plant Nutr 21:2718–2738
Zhang Y, Schaap MG (2019) Estimation of saturated hydraulic conductivity with pedotransfer functions: a review. J Hydrol 575:1011–1030
Zhang L, Jing Y, Chen C, Xiang Y, Rezaei Rashti M, Li Y, Deng Q, Zhang R (2021) Effects of biochar application on soil nitrogen transformation, microbial functional genes, enzyme activity, and plant nitrogen uptake: a meta-analysis of field studies. Gcb Bioenergy 13:1859–1873
Zhang Y, Ma W, Sun X, Jiang J, Li D, Tang G, Xu W, Jia H (2023) Biochar aged for five years altered carbon fractions and enzyme activities of sandy soil. Land 12:645
Zhou S, Jiang Z, Shen J, Yao Q, Yang X, Li X, Awasthi MK, Zhang Z (2023) Biochar-amended compost as a promising soil amendment for enhancing plant productivity: a meta-analysis study. Sci Total Environ 879:163067