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Review

The Biological Effects of Biochar on Soil's Physical and Chemical Characteristics: A Review

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Abstract: Owing to its high pH, nutrient content, porous structure, and strong adsorption properties, biochar is an effective soil amendment. The application of biochar to soil represents an effective strategy for ameliorating the environmental conditions in soil, enhancing its fertility, promoting plant growth, and mitigating pollution in soil. However, the specific mechanisms underlying the changes in soil's physicochemical properties that are induced by the application of biochar remain unclear. For this article, we reviewed and analyzed the literature on the impact of biochar application on soil's physicochemical properties over the past 20 years, exploring the effects of biochar on eight key physicochemical indicators of soil, including soil aggregates, bulk density, pH, and electrical conductivity. Based on our analysis of multiple experimental results from various articles, this article provides an overview of these effects. A wide range of researchers have elucidated the application and mechanisms of the impact of biochar. This study reveals that the application rate of biochar, the type of feedstock, and the pyrolysis temperature are the main factors influencing the effectiveness of biochar in improving soil's physicochemical properties. Furthermore, these improvements are influenced by soil's texture and environmental conditions. Overall, these findings highlight the importance of considering multiple factors when utilizing biochar for soil enhancement.

Keywords: biomass; physicochemical property; agriculture; biochar

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1. Introduction

Because of its exceptional carbon sequestration ability, biochar has attracted the attention of researchers within various fields. Biochar is usually a solid black material produced from organic matter through pyrolysis in a low-oxygen environment. Globally, the annual biomass production from various sources is nearly 10 billion tons [1], providing ample raw materials for biochar production. Biochar contributes to soil improvement, enhances the soil's fertility, reduces greenhouse gas emissions, adsorbs heavy metals, and can be used for remediating soils, such as by removing organic pollutants [2], thereby facilitating new pathways for the efficient use of agricultural and forestry waste. Furthermore, biochar can enhance the physical and chemical properties of soil by enhancing its existing characteristics, making it a promising soil amendment that improves crop growth [3], increases yields and carbon sequestration, and reduces emissions. Therefore, investigating the impact of biochar on the physical and chemical properties of soil is important to address issues relating to improving the soil's fertility, reducing greenhouse gas emissions, increasing crop yields, and promoting sustainable agricultural development.

For this article, we comprehensively reviewed the literature on how biochar affects the physical and chemical properties of soil, discussed several key effects in detail, and analyzed experimental results to identify mechanisms by which biochar affects soil's properties, such as its aggregate stability, bulk density, pH, and electrical conductivity (EC). We found that biochar reduces the soil's bulk density, enhances its aggregate stability, improves soil moisture management in arid areas, raises the pH of acidic soils, and increases the amount of soil nutrients. Additionally, the potential mechanisms by which biochar influences various soil properties are summarized. For instance, the higher specific surface area and porosity of biochar can improve the structure and aggregate stability of soil, thereby enhancing nutrient utilization, increasing the soil's porosity and aggregate content, and reducing its bulk density. The acidity of biochar's surface and the presence of oxygen-containing functional groups can alter the hydrophobicity of the soil and improve its moisture content. The application of biochar can enhance the cation exchange capacity of soil, allowing it to more effectively adsorb and release nutrients, thereby supporting the development of sustainable agriculture. According to the existing literature, the impacts of biochar on soil's physicochemical properties are primarily reflected by eight indicators: the soil's bulk density, aggregation, porosity, moisture content, cation exchange capacity, pH, nutrients, and electrical conductivity. Studies have shown that biochar application typically results in a significant reduction in the soil's bulk density and improves its aggregate structure, showing more pronounced effects in sandy clay soils and under arid conditions. Additionally, the appropriate application of biochar can significantly improve the soil's moisture retention capacity; in soils with higher sand contents, the porosity tends to increase with further biochar application. Under specific soil conditions, such as in acidic soils, biochar can raise the soil's pH and enhance its nutrient availability and cation exchange capacity. However, these effects may vary depending on the initial state of the soil, the type of biochar that is applied, and the application rate. Meanwhile, changes in the soil's electrical conductivity may be influenced by its background salinity and moisture conditions, providing insights for future research on how biochar affects soil characteristics.

Despite the substantial amount of research exploring the impact of biochar on the physicochemical properties of soil, these studies often focus on specific crops or soil types, meaning that a comprehensive analysis of the broader applicability of biochar under different environmental conditions is lacking. Additionally, the specific mechanisms by which biochar affects the characteristics of soil remain unclear, leading to an insufficient understanding of its applications. This review aims to fill the following research gaps: on the one hand, the aim is to systematically assess the comprehensive effects of biochar on different soil types; on the other hand, the aim is to analyze the physical and chemical mechanisms of biochar in depth to reveal its potential mechanisms for improving soil's properties (Figure 1). By integrating the latest experimental results, we hope that this study will provide a theoretical foundation for future research and offer scientific justification for the broader application of biochar. The purpose of this paper is not only to review the existing literature relating to biochar but also to provide a comprehensive overview to promote its application in the context of sustainable agricultural development. Understanding the multidimensional impacts of biochar on the physicochemical properties of soil will aid in the formulation of more effective soil management strategies and advance the development of ecological agriculture.

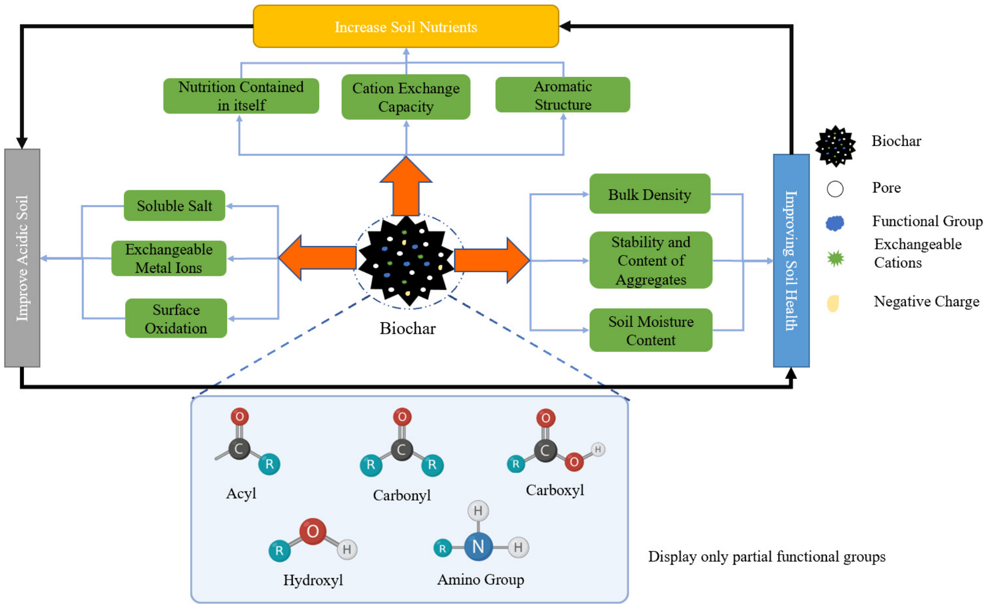


Figure 1. Diagram of biochar's mechanisms of impact.

2. Materials and Methods

2.1. Data Collection

We built a bibliometric database based on the Web of Science (WOS) core collection, using the keywords "biochar", "black carbon", or "charcoal" in conjunction with "soil physicochemical properties". This search allowed us to identify publications containing these terms in their title, abstract, authors, keywords, or additional keywords and to retrieve data on the number of journals, publication types, and publication years.

The data collection can be divided into the following parts:

1. Types of literature, language, and country of publication.
2. Annual publication number from 2000 to 2023.
3. The distribution of publications based on subject category and journal.
4. Research hotspots and future trends.

2.2. Data Analysis Methods

After ranking the retrieved publications based on their relevance, they were screened to include only papers, review papers, and conference proceedings, primarily from the years 2000 to 2023. The literature screening process followed the following criteria: Relevant keywords (such as "biochar", "soil physical properties", "soil chemical properties", etc.) were searched in the scientific database within the selected time range while excluding conference proceedings, editorials, and studies with low relevance. Further screening was conducted based on several specific criteria, including their relevance (assessed by reviewing titles and abstracts to exclude articles with low relevance), citation frequency (determined by selecting articles with high citation rates within the relevant research field to ensure a focus on research with significant academic influence), and quality (assessed by prioritizing high-quality journal articles). After the screening, a final sample of 3000 highly relevant and frequently cited articles was established for analysis, examining multiple dimensions such as the countries of publication, authors, distribution of keywords, and timelines to comprehensively identify the research dynamics in this field.

In this article, we primarily analyze the effects of biochar application on eight key physical and chemical indicators: the soil's bulk density, aggregate stability, porosity, moisture content, cation exchange capacity, pH, nutrients, and electrical conductivity. The selected articles include biochar types that are derived from different materials, such as wood, bamboo, straw, and birch. Additionally, biochar produced at various pyrolysis temperatures (ranging from 300 °C to 700 °C) is included.

3. Results

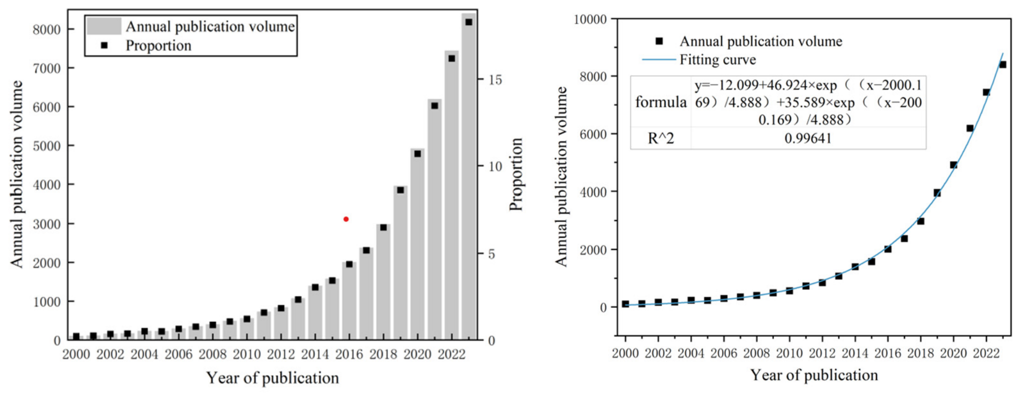
3.1. Data Analysis

A total of 43,874 papers from between 2000 and 2023 regarding the impact of biochar on soil's physical and chemical properties were retrieved from 200 journals (Table 1). Of these, 43,425 (87.549%) were original research papers, reflecting the significant research focus on the influence of biochar on the physical and chemical properties of soil. We performed a statistical analysis of the original research papers on the effects of biochar application on key parameters of soil's physical and chemical properties. The results showed that articles relating to soil's pH accounted for 33%; for soil nutrients, this number was 22.9%, while for soil's bulk density, it was 15.7%; for soil aggregates, it was 10.4%, and for soil's moisture content, the number was 7.3%; papers relating to soil porosity accounted for 6.5%, while papers on soil's cation exchange capacity (CEC) accounted for 3.3%, and those relating to soil's conductivity accounted for 0.8%. Additionally, there were 1801 conference proceedings, 1271 review articles, 467 book chapters, and 2637 papers that were classified as "other types", including reports, editorials, and retracted publications.

Table 1. Types and numbers of published papers from 2000 to 2023.

Document Type	Number of Papers	Percentage
Research Paper	43,425	87.55%
Conference Proceeding	1801	3.63%
Review Article	1271	2.56%
Book Chapter	467	0.94%
Others	2637	5.32%

The annual publication numbers revealed an exponential growth based on nonlinear fitting (Figure 2). From 2000 to 2010, only 3102 papers were published, accounting for 6.604% of all publications. Between 2011 and 2015, there was a significant increase in the number of publications, with 5615 papers being published (11.954% of the total). During this period, the average annual number of papers rose from 282 to 1123. Between 2016 and 2023, the annual publication rate increased further, averaging 4394.6 papers per year (accounting for 81.441% of all publications).



(**a**) (**b**)

Figure 2. The annual number and percentage of papers published from 2000 to 2023 (**a**) with a nonlinear fitting displayed (**b**).

The majority of the retrieved results (96.713%) were in English (Table 2), while there were significantly fewer publications in Chinese (28, 0.065%). However, papers published from China made up 38.771% of all publications (Figure 3), totaling 18,336 papers. The USA followed closely behind with 6788 papers, accounting for 14.353% of all papers. All other countries collectively contributed <10% of all published papers.

Table 2. Number and proportion of publications by language from 2000 to 2023 (only the first 7 are shown).

Rank	Language	Number of Papers	Percentage
1	English	41,396	96.505
2	Portuguese	1084	2.527
3	Spanish	267	0.622
4	French	42	0.098
5	German	42	0.098
6	Polish	36	0.084
7	Chinese	28	0.065

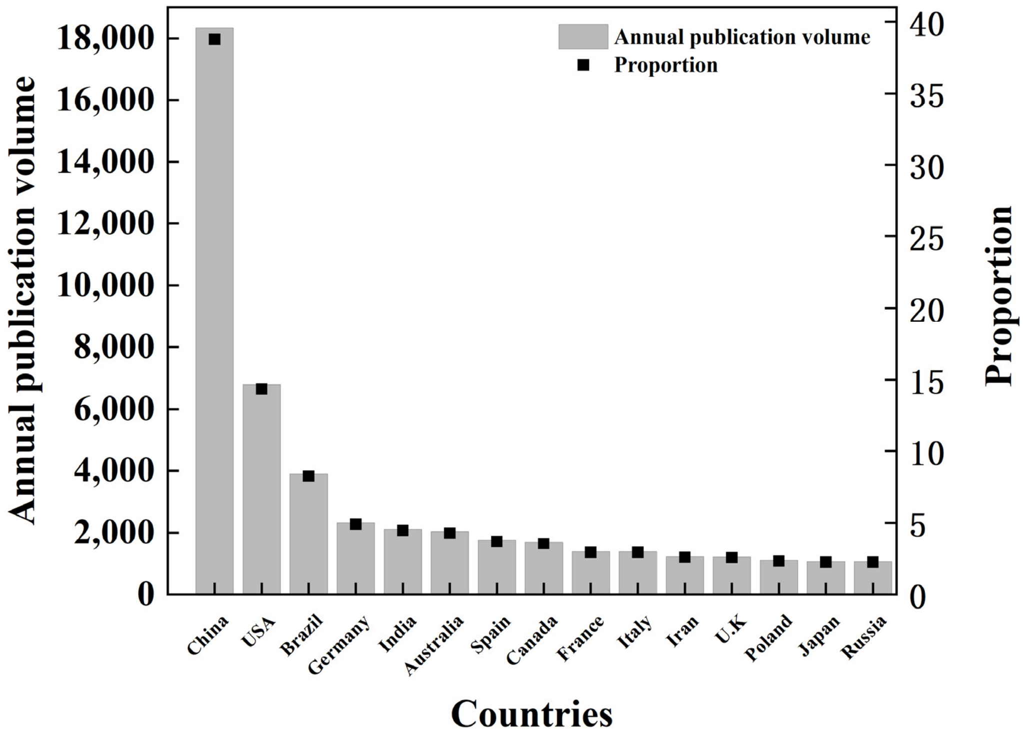


Figure 3. Total numbers of publications by country from 2000 to 2023 (only the top 15 are shown).

Research on the effects of biochar on soil's physical and chemical properties has mainly been published in journals relating to environmental science, energy, fuels, and agriculture. Because of the large number of retrieved results, a subset of 974 of these were analyzed. The top five journals (ranked by their total citation counts) were Bioresource Technology (16,788), Chemosphere (10,864), Chemical Engineering Journal (9869), Journal of Hazardous Materials (7549), and Science of the Total Environment (7517) (Table 3). The five journals with the highest numbers of published papers were Science of the Total Environment (1669 papers), Atmospheric Chemistry and Physics (1216 papers), Atmospheric Environment (1026 papers), Bioresource Technology (989 papers), and Chemosphere (974 papers) (Table 4). The primary research directions within the wider research area of the impact of biochar on soil's physical and chemical properties include environmental engineering, atmospheric science, agriculture, and energy (Table 5).

Table 3. Citation analysis of highly cited articles.

Rank	Source Title	Total Citations	Total Number of Papers
1	Bioresource Technology	16,788	90
2	Chemosphere	10,864	47
3	Chemical Engineering Journal	9869	83
4	Journal of Hazardous Materials	7549	79
5	Science of the Total Environment	7517	70
6	Environmental Science & Technology	6579	24
7	Atmospheric Chemistry and Physics	5645	28
8	Renewable and Sustainable Energy Reviews	4593	20
9	Journal of Geophysical Research: Atmospheres	3876	6
10	Soil Biology & Biochemistry	3585	18
11	Geoderma	3400	20
12	Journal of Cleaner Production	3159	35
13	Water Research	3139	20
14	Proceedings of the National Academy of Sciences of the United States of America	2711	10
15	Global Change Biology Bioenergy	2701	10
16	Plant and Soil	2378	11
17	Fuel	1959	16
18	Environmental Pollution	1930	15
19	Scientific Reports	1723	10
20	Nature	1587	3

Table 4. Number of articles published by various journals.

Rank	Publication Title	Number of Papers	Percentage
1	Science of the Total Environment	1669	5.27
2	Atmospheric Chemistry and Physics	1216	3.84
3	Atmospheric Environment	1026	3.24
4	Bioresource Technology	989	3.12
5	Chemosphere	974	3.07

Table 5. Research directions and number of publications.

Rank	Research Direction	Number of Papers	Percentage
1	Environmental Sciences; Ecology	15,371	48.51
2	Engineering	7156	22.59
3	Meteorology; Atmospheric Sciences	5035	15.89
4	Agriculture	4845	15.29
5	Energy; Fuels	3673	11.59

3.2. Cluster Analysis

Using the bibliometric analysis software CiteSpace 6.1.R2, we analyzed research articles published from 2013 to 2023 on the impact of biochar on soil's physical and chemical properties. The literature was meticulously screened to exclude conference proceedings, editorial materials, and less relevant studies, resulting in a sample of 3000 articles with high relevance and citation frequencies for analysis. Our analysis included the country of publication, authors, keyword distributions, and timelines.

In the map provided in Figure 4, nodes represent different countries or researchers, while connections between nodes indicate collaborative relationships between them. The width of a line connecting nodes reflects the extent of collaboration, with wider lines indicating more connections and greater collaboration. Surrounding the nodes are purple circles, indicating that a node exhibits brokerage centrality. The wider the bands are, the stronger the brokerage centrality is, signifying that the node serves as an important hub connecting different fields.

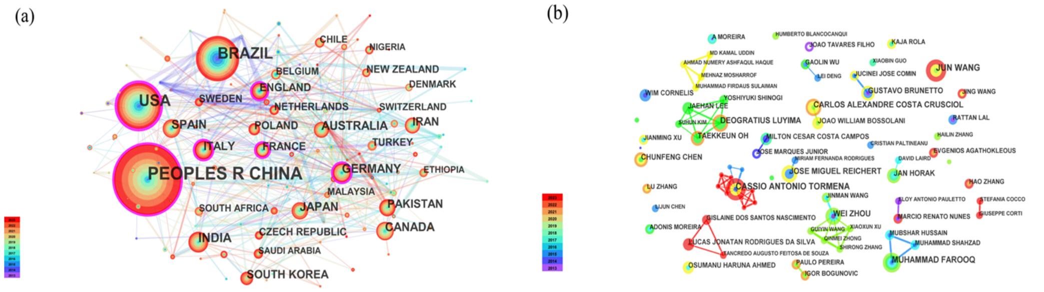


Figure 4. The co-occurrence map of research countries (**a**) and authors (**b**) studying the effects of biochar on soil's physical and chemical properties from 2013 to 2023.

Scrutinizing the publication statistics between 2013 and 2023 enabled us to analyze the differences in research output between countries. The three countries with the highest publication outputs from 2013 to 2023 are China, the USA, and Brazil (Table 6), with China having published 956 articles—2.17× that of the USA and 2.33× that of Brazil. The brokerage centralities for China (0.17), the USA (0.35), India (0.11), and Germany (0.19) all exceed 0.1, indicating that these countries have a considerable global influence in this field. The values for the USA and Germany both exceed that of China; although the USA and Germany have published fewer papers than China, their influence is greater, possibly because China is a relative latecomer to this research discipline. The nodes between countries are closely connected with several links, indicating a high degree of collaboration (Figure 2). Specifically, authors in China collaborated with authors in 55 countries, whereas authors in the USA collaborated with authors in 73 countries.

Table 6. The number of papers originating in various countries and cooperation characteristics in research on biochar's impact on the physical and chemical properties of soil, 2013–2023.

Rank	Country	NPs	NCCs	BC
1	China	956	55	0.17
2	America	441	73	0.35
3	Brazil	411	45	0.09
4	India	125	33	0.11
5	Canada	107	30	0.06
6	Germany	107	58	0.19
7	Spain	107	42	0.07
8	Australia	102	42	0.07
9	Japan	93	33	0.07
10	Italy	89	39	0.06

NPs: number of papers; NCCs: number of cooperating countries; BC: betweenness centrality.

Our cluster analysis revealed the main researchers in the field and their research focus. The 3000 most cited articles were authored by 1387 individuals, of which 56 had published ≥4 articles (4.04% of the total) and collectively contributed 283 articles (9.43%). These authors made significant contributions to the research in this area. Several authors had also published fewer than four articles, which reflects the emerging nature of this research field since 2013, prompting numerous researchers to invest resources into the exploration of this domain.

A visualized keyword timeline was created using annual time slices based on keyword clusters (Figure 5). The numbers on the right side of Figure 6 correspond to the keyword cluster numbers, and the timeline chart details the emergence of various keywords in clusters and their correlation with research trends in the field. Research topics such as soil's bulk density, organic matter in soil, crop yield, and soil microorganisms emerged relatively early, while studies on soil's pH, enzyme activity, and effective water content appeared later. Overall, the research output on the impact of biochar application on soil's physical and chemical properties has remained consistently high.

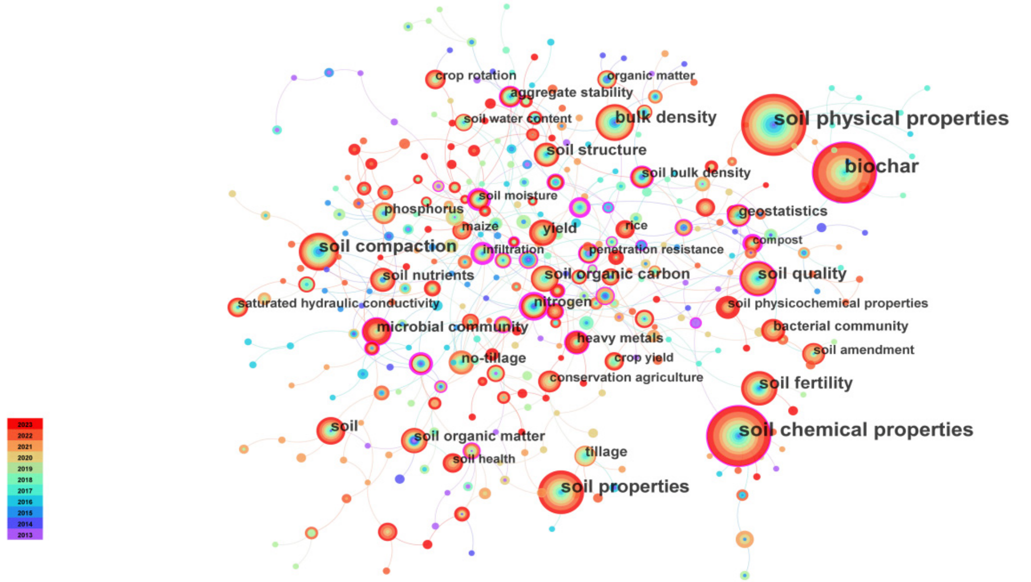


Figure 5. Cluster analysis of keyword co-occurrence in research on the influence of biochar on soil's physi-cochemical properties, 2013–2023.

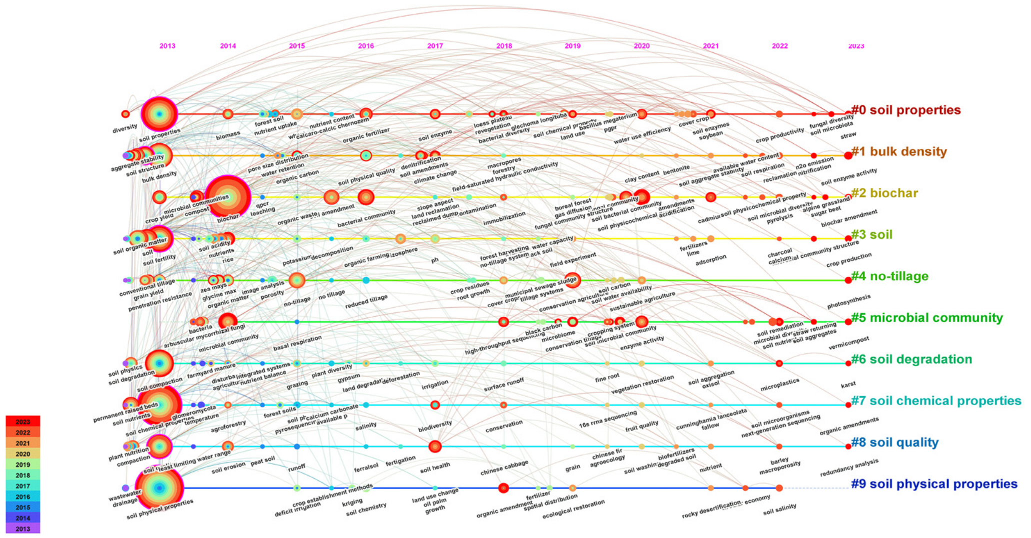


Figure 6. The publication time of keyword co-occurrence of research on the influence of biochar on soil's physicochemical properties from 2013 to 2023.

Keyword clustering is a method that uses statistical techniques to compute, summarize, and synthesize keyword data. Clustering analysis evaluates the reliability and reasonableness of clustering results based on two indicators: modularity (Q) and average silhouette width (S). A Q value > 0.3 indicates that the cluster results are reasonably reliable, and an S value > 0.5 suggests strong homogeneity among the keywords within a cluster, indicating a robust clustering effect and reliable results. An S value > 0.7 indicates that the cluster results are trustworthy. Our cluster results yielded Q = 0.4909 and S = 0.7401, indicating that the results are reliable and that the clustering effect is strong. The keyword cluster depicts the impact of biochar application on soil's physical and chemical properties (Figure 6), with the research being focused on indicators such as the soil's porosity, bulk density, aggregates, EC, pH, microorganisms, and organic matter. Consequently, we reviewed these effects.

3.3. Effects of Biochar on Soil's Physical Parameters

The main physical indicators of soil properties are the soil's porosity, bulk density, moisture content, and aggregates. The soil porosity is a metric of the soil's structure and pore conditions, which play important roles in plant root growth and nutrient absorption. The bulk density of soil is the mass (or weight) of undisturbed soil per unit volume [4]; it characterizes soil's ecological function and serves as an indicator of its quality [5,6]. An excessive bulk density can reduce aeration in the soil, impede nutrient transformation, and adversely affect crop growth. The soil's moisture content is important in agricultural production, with the two most important metrics being its saturation capacity and field water holding capacity. Soil aggregates indicate the soil's fertility, and their stability is a key factor in soil's structure and erosion resistance [7]. Fertility can be evaluated using the aggregate mean weight diameter, geometric mean diameter, and fractal dimension, which significantly influence the ecological functions of flora, fauna, and microorganisms. The effects of biochar application on soil's physical properties are illustrated in Figure 7.

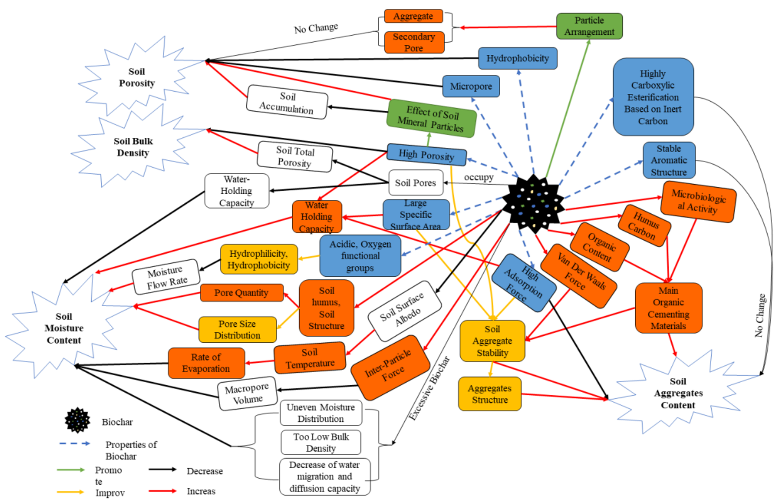


Figure 7. Mechanisms by which biochar improves soil's physical properties.

3.3.1. Soil Porosity

Biochar is rich in nanoscale micropores [8] and has a low density. When incorporated into the soil, its high adsorption and expansion capabilities [9] enhance soil aggregation and improve the soil's structure [10]. Additionally, biochar interacts with mineral particles in soil to reduce soil compaction [11], thereby creating further porosity [12] and decreasing the soil's bulk density (thus increasing its porosity). The total soil porosity is greater with higher amounts of biochar and increased sand content [13]. Furthermore, biochar that is produced at medium temperatures (250–500 °C) and under laboratory conditions more effectively enhances the soil's porosity. The effect of biochar on soil porosity is influenced by numerous factors (Table 7), including the application rates (ranging from 0.1% to 30%), pyrolysis temperatures (400–600 °C), soil type (e.g., silica sand, sandy soil, sandy loam, loamy soil, clay, and silt), and the base material of the biochar. Depending on the experimental conditions, biochar can increase the soil's porosity by 2–41%, although the lack of any significant difference in effective porosity [14] may be because biochar is hydrophobic, the small size of biochar pores, or because of a combination of both, creating resistance to water flow dynamics.

The application of biochar can increase the porosity and reduce the bulk density, but the promoting effect on porosity may vary depending on the soil's texture and biochar's characteristics. Different sizes of biochar particles have varying effects on the soil's porosity. For instance, Glab et al. found that the total porosity was not significantly affected by Miscanthus biochar of different particle sizes (0.5–2 mm), but in loamy soil, the total porosity increased with the addition of biochar [15]. Duarte et al. observed that the total porosity in sandy soil improved with the addition of biochar particles sized 0.15–2 mm, although the increase was not significant [16]. Research by Fu et al. indicated that applying biochar particles of various gradients significantly increased the soil's porosity [17]. Fine biochar particles filled the spaces between coarse soil particles, increasing the number of medium and fine pores and significantly altering the distribution of soil pore sizes while also enhancing the porosity and reducing the soil's bulk density. Additionally, different soil textures exhibit varying degrees of aggregation; for example, clay soils typically have a stronger aggregated structure, whereas sandy soils have weaker aggregation. The promoting effect of biochar application on clay soil aggregates is stronger than that on sandy soil. The formation of soil aggregates helps improve the physical structure of the soil and increases its porosity.

Villagra-Mendoza et al. [18] reported that increasing the amount of biochar did not significantly affect the overall porosity, but it did reduce the total porosity of sandy soil by up to 3%. This was mainly attributed to the rearrangement of particles and formation of aggregates and secondary pores following the incorporation of biochar, resulting in negligible changes in the overall porosity. Wang et al. [19] reported significant differences in the surface layer (0–20 cm) porosity of soil following biochar application, although the differences in porosity from 20 to 40 cm were not always significant, possibly because of incomplete mixing of the soil and biochar during tilling.

Table 7. The effect of biochar application on the total porosity in the top 15 cm soil layer under different conditions.

No.	Soil Texture	Experimental Environment	Cultivation Duration (Months)	Biochar Type	Pyrolysis Temperature (°C)	Application Rate (%)	Increase in Porosity (%)	References
1	Silica Sand	Laboratory	NR	Leguminous Shrubs	400	0 2% 4% 6% 8% 10%	12–41	[14]
2	Sandy Soil	Laboratory	6	Rice Hulls	~600	0% 0.10% 0.50% 1%	7 14 18	[20]
	Sandy Loam	Laboratory	6	Rice Hulls	~600	0% 0.10% 0.50% 1%	8 11 13	

Table 7. *Cont.*

No.	Soil Texture	Experimental Environment	Cultivation Duration (Months)	Biochar Type	Pyrolysis Temperature (°C)	Application Rate (%)	Increase in Porosity (%)	References
3	Sandy Loam, Loamy Sand, Sand Soil	Field	12	Corn Cobs, Rice Hulls	350	0–4%	2–12	[21]
4	Loamy Sand	Greenhouse	3	Miscanthus × Barley, Winter Wheat	300	0.50% 1% 2% 4%	 5 12 24	[15]
5	Clay	Field	24	Corn Residue	400	0 Mg ha^{-1} 10 Mg ha^{-1} 20 Mg ha^{-1} 30 Mg ha^{-1}	 13	[22]
6	Silty Clay	Field	3	Wheat Bran	 800 1200	0 Mg ha^{-1} 14 Mg ha^{-1} 14 Mg ha^{-1}	 7	[10]

"NR": not reported.

Most of the research findings come from laboratory and greenhouse studies and may differ from those of field experiments. Both laboratory and greenhouse research aim to strictly control variables and minimize the impact of different climatic conditions on the experiments. However, these findings need to be validated in field environments, with strict monitoring of conditions that cannot be simulated in laboratory studies to ensure their applicability. By establishing field trials to compare the effects of different treatments (such as the amount and type of biochar) on soil characteristics and crop growth, we can better assess the transferability of the laboratory results. Additionally, in field studies, local climatic conditions, soil types, and existing soil management practices must be considered, as these factors can significantly affect the efficacy of biochar. Long-term monitoring is also crucial to understand the lasting impacts of biochar on soil characteristics and crop productivity. Multidisciplinary collaboration will help to comprehensively understand the relationship between laboratory findings and field applications, thereby promoting the practical use of biochar in sustainable agriculture.

3.3.2. Soil's Bulk Density

Following the application of sugarcane straw biochar by Raiz et al. [23], the soil's bulk density significantly decreased from 1.17 g cm^{-3} to 1.09 g cm^{-3}. This reduction was likely because of the well-developed pore structure of biochar, which may enhance soil aggregation and interact with the soil's pore structure to create a more favorable soil structure [9], thus decreasing its bulk density. Additionally, the decrease in the soil's bulk density is influenced by the amount of biochar that is applied. For instance, Wang et al. [19] reported significant differences in the soil bulk density reduction rates following various rates of biochar application, with the smallest reduction in the soil's bulk density being 3.42% when the biochar was applied at 9 kg m^{-2}. The effects of biochar amendment are also affected by the raw materials that are used in its production. Yi et al. [24] reported pine biochar to have better amendment effects than poultry manure-based biochar, with greater improvement rates following from increased application rates. Additionally, the pyrolysis temperature affects biochar's effectiveness; biochar that is produced at higher temperatures (>500 °C) reduces the soil's bulk density more than that produced at lower temperatures (<500 °C) [25].

Duarte et al. reported a decrease in the particle size of biochar to increase the bulk density of soil, mainly because smaller biochar particles occupy some soil pores, reducing the total porosity and increasing the bulk density. Singh et al. [25] reported that wood, herbaceous material, and woody waste biochars all significantly reduced the bulk density of soil, but the differences between the biochar types were not statistically significant. Horiák et al. [9], however, concluded that the application of biochar did not significantly reduce the soil's bulk density. These differences may be because field trial conditions are subject to greater uncontrolled environmental variability than laboratory conditions are. Zhao et al. [26] reported that biochar derived from corn straw at different pyrolysis temperatures did not significantly affect the soil's bulk density. Similarly, Liu et al. [27] concluded that the biochar type and preparation temperature did not influence the bulk density of soil. The primary reason for these observations is that the bulk density of biochar that was produced under various conditions was relatively close to that of the soil, resulting in no significant reduction in the soil's bulk density.

3.3.3. Soil's Moisture Content

Because of the high porosity of biochar [28], its strong adsorption capacity, and its large specific surface area [29], it significantly improves the structure of soil and enhances its water retention capacity [30]. Biochar's surface is also rich in acidic and oxygen-containing functional groups [31], which can alter its hydrophilic and hydrophobic properties [32], slowing the movement of moisture within soil [33]. This improves the soil's moisture content and demonstrates that biochar can significantly affect soil water management. Song et al. [34] tested biochar treatments over a two-year period and reported that they increased the average annual soil moisture by 5.95% (at 5 t ha^{-1}) and 9.8% (at 15 t ha^{-1}). The improvement in soil moisture management that can be attributed to biochar is influenced by multiple factors. Ibrahimi et al. [35] compared the effects of various conditions on the soil's available water capacity (AWC) and reported the particle size and specific surface area of the biochar, the application rate of biochar, the soil's texture and pH, and the experimental environment to significantly improve the soil's moisture content. Additionally, Horiák et al. [9] reported that the application of biochar significantly and positively affected the moisture content, field capacity, and available water capacity of loamy soil. This improvement was attributed to the increase in soil humus and changes in the soil structure following biochar application. The number of larger micropores in the soil increased, resulting in a change in the pore size distribution, enhancing the field capacity and increasing the AWC of the soil [36].

The impacts of biochar application are not universally beneficial. For instance, some unstable biochars can rapidly decompose, bind together, and clog soil pores when they are applied to the soil, adversely affecting the movement of water within the soil and decreasing its water retention capacity [37]. Yan et al. [38] reported that the overall application of biochar increased the moisture content in soil and that this improvement was significantly greater at 185 d and 215 d at a lower (40 t ha^{-1}) application rate than at a higher one (60 t h^{-1}). This suggests that within a certain application range, biochar can effectively alleviate moisture stress. However, the excessive application of biochar can lead to an overly low soil bulk density, which may hinder water retention. Fu et al. [39] reported consistent but gradually diminishing increases in the soil's moisture content with the increased application of biochar. This suggests that higher application rates of biochar increasingly inhibited the migration and diffusion of moisture in the soil. Castellini et al. [40] reported no significant differences in the saturated and unsaturated hydraulic conductivity of the soil after biochar application, but notable reductions in the AWC and relative field capacity were found. This may be because moderately swollen soil particles in saturated conditions alter the bonding forces between particles and cause larger pore volumes. Additionally, with the increased application of biochar, the soil's wettability gradually decreases, leading to an uneven distribution of soil moisture in the root zone that can decrease the values of various indicators. Graef et al. [41] reported that biochar reduced the soil's moisture content under conditions of ridge cultivation—a phenomenon that can possibly be attributed to dark-colored biochar decreasing the surface soil's albedo and thus increasing soil temperatures [42], leading to elevated rates of soil evaporation and reduced soil moisture levels.

3.3.4. Soil Aggregates

Biochar has well-developed porous structures, a high specific surface area, and strong adsorption capabilities, which significantly enhance the aggregate stability and improve the aggregate structure of soil. Sharma et al. [43] reported that the application of 2 t ha^{-1} of biochar to subtropical soil aggregates significantly increased the aggregate stability by 8.1%. This improvement was attributed to biochar's ability to enhance the microbial activity in soil, boosting this activity to produce more gluing substances and increasing the aggregate quantity and stability [44]. Additionally, biochar application elevates the organic matter and humic carbon contents in soil—two key organic binding agents that promote the formation and stabilization of soil aggregates, increasing the aggregate content and enhancing its stability [45,46]. Chen et al. [47] reported that biochar significantly increased the aggregation of particles >0.25 mm and decreased that of particles <0.25 mm. This effect can be attributed to positive and negative charges on the biochar surface, which directly bind with mineral particles to form larger aggregates and promote the formation of larger aggregates by adsorbing smaller microaggregates. The biochar application rate is also a contributing factor. For example, Omondi et al. [13] reported increases in the soil's aggregate stability of 5.3% at 41–80 t ha^{-1} and 9.7% at >80 t ha^{-1} application rates. However, the application of biochar does not always significantly affect the soil's aggregate stability. Hardie [48] suggested that this may be because biochar that is made from acacia green waste containing a highly carboxylated and stable aromatic structure, predominated by inert carbon [49], is difficult for microbes to decompose and use. The organic matter content of soil can also alter the ameliorative effects of biochar; Parker et al. [50] reported that when the natural organic matter content of soil was sufficiently high (2.3%), straw biochar did not significantly affect the soil's aggregate stability under slow wetting conditions.

The effectiveness of biochar in improving soil aggregates is influenced by the soil's texture. Blanco-Canqui reported that the application of biochar enhanced the stability of water aggregates in 24 soil types, with improvements correlating with the amount of biochar that was applied. Additionally, the mean weight diameter increased by 4–58%, and the proportion of water-stable aggregates increased by 21–226%. Biochar application improved the non-water aggregate stability in silty loam, sand, and sandy loam soils but had no great effect on 10 other soil types from various regions. Wang et al. [51] reported that biochar application did not significantly affect the aggregate stability in sandy loam soil, but it did significantly improve silty loam's aggregate stability. While biochar application also increased electrostatic repulsion and van der Waals forces within the soil, the increases in these attractive forces outweighed the repulsive forces, and the soil's aggregate stability was enhanced [52].

3.4. Effects of Biochar on Soil's Chemical Parameters

In exploring the role of biochar in soil improvement, the physical and chemical effects are interconnected. Soil porosity and moisture retention capacity directly affect the nutrient availability and cation exchange capacity. This means that by enhancing the physical properties of soil, we can not only improve water retention but also create more favorable conditions for the chemical effects in the soil. The chemical indicators of soil reflect the influence of biochar on the chemical processes in the soil. Common chemical indicators of soil indicate chemical properties such as the EC, pH, cation exchange capacity (CEC), and nutrient content. The soil's EC is a measure of the salinity in the soil and indicates whether salt levels restrict crop growth; optimal EC values benefit plant development. The soil's pH is typically determined based on the concentrations of hydrogen and hydroxide ions. Biochar tends to be alkaline because of changes in its acidic functional groups during pyrolysis. The CEC indicates the soil's ability to adsorb cations. The magnitude of the CEC indicates the soil's fertility retention capacity, which is important for regulating concentrations of soil solutions. The CEC of biochar mainly depends on the quantity and distribution of oxygen-containing functional groups on its surface [53]. When the biochar's CEC exceeds that of the soil, the soil's CEC can be significantly enhanced. Soil nutrients originate from minerals and organic matter; abundant organic matter improves the soil's nutrient-supplying capacity and prevents compaction and salinization. The adsorption and porous structure of biochar can reduce nutrient loss, retain organic matter and nutrients in water, and promote continuous polymerization to form organic substances [54], thereby improving the soil's fertility. The impacts of biochar application on soil's chemical properties are shown in Figure 8.

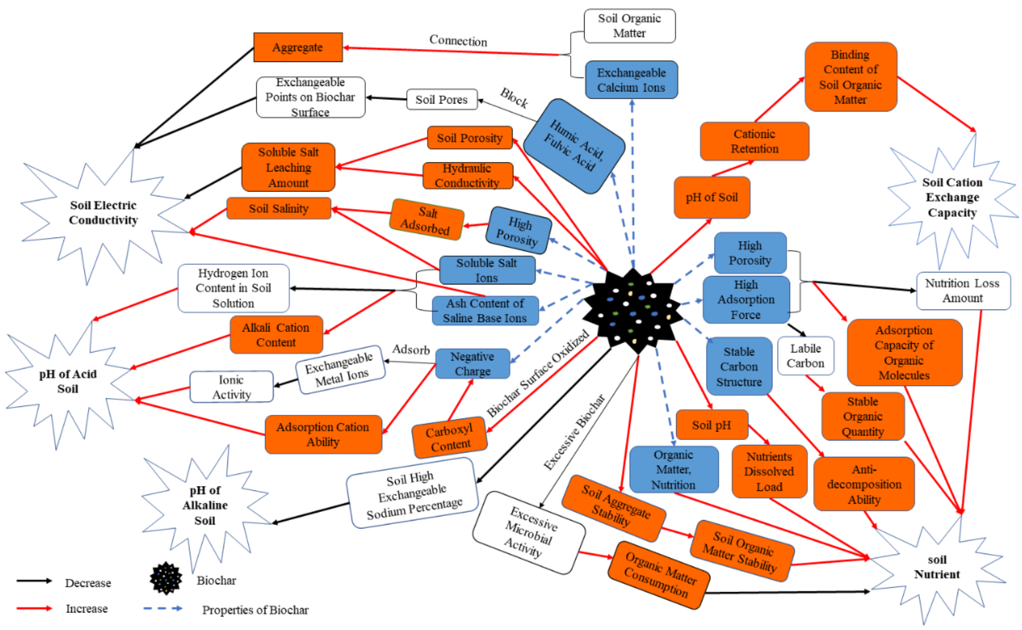


Figure 8. Mechanisms by which biochar improves the chemical properties of soil.

3.4.1. Soil Conductivity

Biochar pyrolysis generates a considerable amount of ash, which contains soluble salt ions such as K^+, Ca^{2+}, and Mg^{2+}. When added to the soil, these ions increase in number, increasing the salt concentrations and the soil's EC. Ehsani et al. [55] and Li [56] reported that the EC increased with increased application of biochar. The type of organic matter that is used to produce biochar also significantly affects the soil's EC. Wang et al. [57] reported that biochar that was produced from straw significantly increased the soil's EC, but biochar produced from wood, bamboo, or walnut shells did not. Singh et al. [25] reported that biochar that was produced from herbaceous materials was more beneficial than that produced from woody materials. This was attributed to the higher ash content of herbaceous biochar, which can exert a more positive influence on the soil's EC [58]. Alidou-Arzika et al. [59] reported that biochar that was produced from the softwood Betula and hardwoods Quercus, Fagus, and Carpinus significantly increased the soil's EC, but not that of Pinus, possibly because pine biochar had a lower salt content that did not leach into the soil. Singh et al. [25] reported that notable increases in the soil's EC only occurred under specific conditions, such as when the biochar was applied to finely textured soils and produced at lower temperatures (<500 °C) or when higher application rates (>80 t ha^{-1}) were used. Even when using biochar that was produced from the same species, the biochars that are produced from different parts of that species can vary in their impacts on the soil's EC. Hilioti et al. compared the effects of using castor bean cakes and castor straw biochar and reported that only the 5% straw biochar treatment showed a significant increase compared with a 1% increase following straw biochar treatment and that no significant differences were observed following the bean cake treatments. Temperature is also an important factor, with Yoo et al. [60] reporting that with an increased pyrolysis temperature, the ability of brewer's spent grain biochar to improve the soil's EC decreased, which correlates with the lower EC values from various pyrolysis temperatures. The influence of soil texture is also significant, with Abujabhah et al. [61] reporting that the application of different ratios of biochar to black clay loam, red soil, and brown sandy loam yielded no significant differences. Liang et al. [62] reported that the addition of biochar to the soil surface and crop rhizosphere in saline–alkali land significantly reduced the soil's EC values. This effect was attributed to biochar's improvement of the soil's porosity and hydraulic conductivity, which accelerated the leaching of soluble salts in saline–alkali soils [63].

3.4.2. Soil's pH

Soil acidification can exacerbate the compaction of soil, reduce its AWC, increase the loss of potassium and magnesium ions and other nutrients, and cause significant dissolution of aluminum and manganese ions. These adverse conditions can hinder crop development and reduce yields. The use of biochar as a soil amendment can yield significant benefits [64]. Biochar's effectiveness is mainly due to soluble salts such as carbonates that are produced during biochar pyrolysis and because biochar ash is rich in various basic cations. These components can bind with H^+ ions in the soil solution, reducing their concentrations [65,66] and significantly increasing the cation content and raising the soil's pH. Yan et al. [67] reported a significant increase in the soil's pH following woody biochar application. Aamer et al. [68] also reported a significant increase in the soil's pH following biochar application, with this effect increasing with the application rate. Biochar's pH is also influenced by the organic matter from which the biochar was produced. Different base materials contain different components, resulting in distinct biochar characteristics during pyrolysis. This variation significantly affects the ability of biochar to improve the soil's pH. For example, Muhammad et al. [69] reported that biochar that was produced from fruit peel, pig manure, and aloe, and rapeseed significantly increased sandy loam soil's pH, but biochar produced from pig manure, followed by fruit peel, was the most effective. Rodríguez-Vila et al. [70] reported that the soil's pH generally increased with the application of biochar that was produced from corn stover, rice husks, and grapefruit wood sawdust in acidic tropical and neutral tropical soils and that the pH also increased with increased pyrolysis temperatures (300 °C, 500 °C, and 700 °C). Contrarily, Singh et al. [25] reported that biochar that was produced at different temperatures had no significant effect on the soil's pH, possibly because the biochar pH values that were produced at different pyrolysis temperatures did not substantially differ from the soil's pH values. Because of its negatively charged surface, biochar can also adsorb a certain quantity of exchangeable metal ions, such as aluminum ions [71]. These ions bind with soluble organic matter in the biochar to become fixed in the soil, reducing their reactivity [72] and increasing the soil's pH. After biochar is applied to the soil, its surface oxidizes, increasing the number of carboxyl groups. This enhanced negative charge improves the capacity of biochar to adsorb cations [73], further contributing to the increased pH of the soil.

Soil salinization can lead to increased soil compaction, greater susceptibility to soil erosion, and reduced microbial activity. The decreased nutrient use, lower organic matter content, and diminished soil fertility resulting from this impair crop development and pose a serious threat to agricultural production. The elevated pH of saline–alkali soils is mainly associated with a high percentage of exchangeable sodium (ESP) [74], suggesting that a reduced pH in salinized soils may be linked to biochar's ability to lower the amount of ESP [75,76]. Additionally, the low initial pH of biochar plays a significant role in the amelioration of saline–alkali soils. For example, Guo et al. [77] applied corn straw biochar (pH 8.42) to improve unfrozen saline–alkali soil (pH 10.29) and frozen saline–alkali soil (pH 10.21) and reported significant reductions in the soil's pH for both (decreasing by 0.11 and 0.05, respectively). Zhou et al. [78] reported that the application of acidic corn straw biochar (pH 4.75) to saline–alkali soils significantly lowered pH, with drops of 0.3 observed at sowing and 1.0 at harvesting times. Therefore, the primary factor influencing the soil's pH is likely to be the difference between the pH of the biochar and that of the soil.

Currently, soil salinization and alkalization are severe. Soils that are excessively salinized and alkaline exhibit characteristics such as a high pH, low organic carbon content, and insufficient soil nutrients, which can reduce crop productivity and the sustainability of plant growth. Li et al. improved the irrigation practices of local saline–alkaline lands using drip irrigation technology, leading to a significant improvement in soil salinization [79]. De Villiers et al. planted halophytes in excessively salinized soils; these plants absorb salts from the soil through their root systems, thereby reducing soil salinization [80,81]. Adding biochar as an amendment is also an important method of increasing crop yields from saline–alkaline land. Research by Liu et al. found that the average response of plant productivity (PPR) to biochar application in saline soils was 29.3%, indicating that biochar amendment can significantly enhance plant growth. Biochar that is produced at temperatures below 350 °C, with a moderate pH (8.0–10.0) and low cation exchange capacity (CEC, $\leq$10 cmol kg^{-1}), has the best promoting effect on plant productivity [82].

3.4.3. Soil's Cation Exchange Capacity

The enhancement of the soil's CEC is influenced by the biochar base material. Martinsen et al. [83] reported that the addition of 30% (on a dry weight basis) of cocoa shell/palm kernel shell and rice husk biochar increased the soil's CEC by 2.5 and 2.31 cmol/kg^{-1}, respectively. Hilioti et al. reported that 1% (on a dry weight basis) of castor stalk biochar significantly improved the soil's CEC by 28.5%, but castor cake biochar produced no significant change. Additionally, the change in the soil's CEC is affected by the pyrolysis temperature that is used during biochar production. Singh et al. [25] reported that biochar produced at temperatures >500 °C affected the soil's CEC most significantly, possibly because the high specific surface area and elevated pH of the biochar generated at these temperatures compensated for the lower CEC associated with a low O/C ratio [84,85]. An improved soil CEC is also influenced by the amount of biochar that is applied. For example, Phares et al. [86] and Pandit et al. [87] reported that the soil's CEC increased with increased biochar application rates. At biochar application rates of 2000 kg ha^{-1}, significant increases (154.07–191.27%) in the soil's CEC were observed [88]. The pH of soil also influences the effects of biochar on the soil's CEC [89]. An increase in pH helps to distribute charges within the soil and enhance cation retention [90], thus improving the soil's CEC via interactions between its organic matter and cation groups [91]. However, Ehsani et al. [55] reported that biochar application significantly decreased the soil's cation content, and Hailegnaw et al. [92] reported that biochar only enhanced the CEC values in seven of ten (mildly acidic fluvo-aquatic, nearly neutral gray, mildly acidic gray, mildly acidic fluvo-aquatic, acidic initial, mildly acidic initial, and mildly acidic low-capacity initial) soil types, while reducing the CEC in three others (high pH fluvo-aquatic, high-cation black, and mildly alkaline black soils). This was attributed to excess exchangeable calcium ions in the biochar forming aggregates with the organic matter in the soil, which reduced the soil's CEC. Kwon et al. [93] reported that the addition of biochar to soils with high organic matter contents (including humic substances and fulvic acid [94]) can lead to pore clogging or competitive adsorption sites, decreasing the number of available exchange sites on the biochar surface and thus lowering the soil's CEC. Furthermore, at pyrolysis temperatures exceeding 661 °C, the quantity of acidic oxygen-containing functional groups and the O/C ratio [95] are reduced, causing a decrease in the biochar's CEC and thus reducing the effectiveness of biochar in enhancing the soil's CEC.

In cases where the application rate of biochar is too high, the balance of organic matter in the soil can be disrupted, especially in soils that are already rich in organic matter. Excessive biochar application may lead to an uneven distribution of other components in the soil (such as free ions and organic matter), thereby affecting its cation adsorption capacity. In specific types of soils, such as clay or certain loams that already have relatively high cation exchange capacities (CECs), increasing the amount of biochar may not significantly enhance the CEC and could even result in a decrease in CEC due to a relative dilution effect. In a study by Sun et al. on the impact of reed straw biochar (RHC) on coastal salinized soils in the Yellow River Delta of China, it was found that RHC significantly reduced the soil's CEC. This was because RHC markedly increased the percentage of exchangeable sodium (ESP) in the soil from 9.46% to 37.76%. High ESP values indicate an increase in the proportion of exchangeable sodium ions (Na^+) in the soil, which can occupy the adsorption sites on soil colloids, thereby reducing the adsorption opportunities for other cations (such as Ca^{2+}, Mg^{2+}, and K^+), which leads to a decrease in the soil's CEC [96].

3.4.4. Soil Nutrients

Biochar application significantly aids the enhancement and transformation of soil nutrients, reducing the need for chemical fertilizers. Biochar has a stable carbon structure and strong resistance to microbial degradation, which increases the amount of soil organic carbon (SOC) and facilitates the accumulation of organic matter. Zhou et al. [97] reported that biochar treatment dramatically elevated the nutrient levels in soil (SOC, available nitrogen, available phosphorus, and available potassium), likely because the biochar was mostly sourced from agricultural and forestry waste and contained a certain amount of organic matter and readily available nutrients. Upon application to the soil, biochar noticeably increases the organic matter content in the soil and enhances the microbial activity associated with readily available nutrients. This interaction promotes nutrient dissolution, increasing soil concentrations. Furthermore, biochar enhances particulate stability through long-term organic–mineral interactions [98], promoting aggregate stability and thereby stabilizing SOC [99]. Ehsani et al. [55] reported that the application of wheat straw (3.75%, *w*/*w*) biochar resulted in a proportional increase (2.7 g kg^{-1}) in SOC. Muhammad et al. [69] reported that biochar enhanced the concentrations of dissolved organic carbon, potassium, and total carbon, with variations in outcomes for different soil nutrients being attributed to the type of biochar that was used (produced from fruit peel waste, pig manure, or aloe). Li et al. [100] reported that biochar application degraded alpine grassland soils and significantly increased the total organic carbon, total nitrogen, and available phosphorus contents. When the biochar had a higher cation exchange capacity, it could enhance the adsorption of $NH4^+$-N and inhibit the conversion of $NH4^+$-N to NO-N [101], contributing to an increase in readily available soil nutrients [86]. The application of biochar reduces the soil's bulk density, facilitates nitrogen fixation, minimizes nitrogen loss [102], increases the activity of nitrifying bacteria, and, by enhancing nitrification, increases the levels of nitrate nitrogen. Biochar's adsorptive properties inhibit unstable carbon in the soil, and by promoting the formation of relatively stable organic matter [103], it increases SOC. The addition of biochar also raises the soil's pH, enhancing the microbial activity and nutrient solubility, and improves the nutrient availability. However, as the biochar application rate increases, higher soil microbial biomasses and intensified activity can accelerate organic matter consumption and decrease the overall organic matter content.

The use of biochar in soil also needs to be carried out with consideration of its degradation process and the accumulation of potential pollutants (Figure 9). Over time, the physical and chemical properties of biochar may change. For example, research by Kumar et al. found that after six months of applying rice husk biochar to soil, the number of oxygen-containing functional groups increased, which facilitated the binding of Zn to the biochar [104]. Furthermore, although biochar has the capacity to adsorb heavy metals, if it is derived from contaminated biomass, it may introduce pollutants such as heavy metals and polycyclic aromatic hydrocarbons. Therefore, it is recommended that future research conduct long-term field trials to regularly monitor the effects of biochar on the soil's quality and plant health, focusing on its long-term impact on heavy metals and other pollutants, and carry out corresponding risk assessments to ensure the safe and effective application of biochar in agriculture.

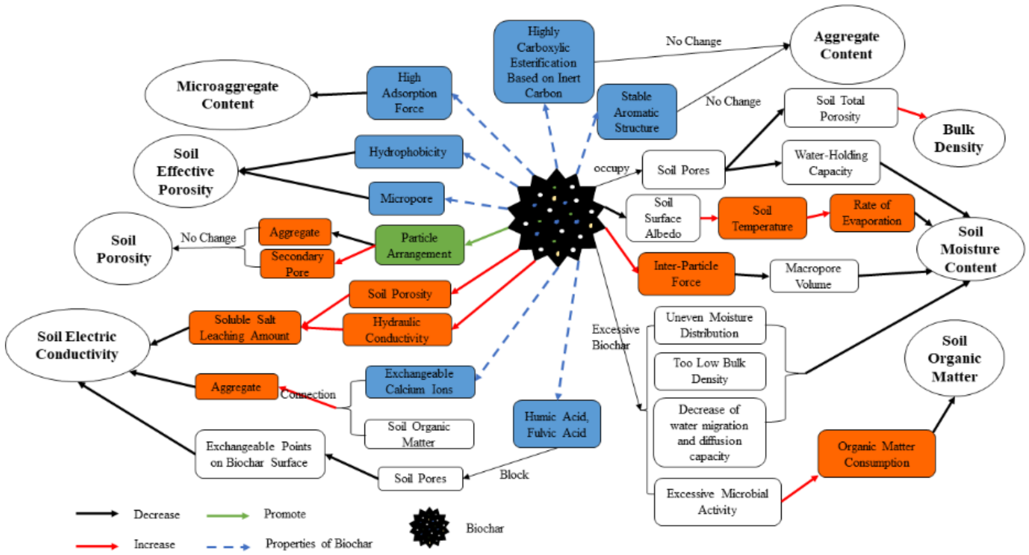


Figure 9. The negative effects of biochar on soil's physical and chemical properties. These effects may include changes in the soil's structure, nutrient availability, and pH levels. It is important to consider these potential drawbacks when using biochar as a soil amendment.

4. Discussion

Our literature review revealed key mechanisms by which biochar improves the physical and chemical properties of soil.

Biochar significantly improves the soil's structure and aggregate stability by leveraging its physical and chemical properties, including a high specific surface area and porosity. It boosts soil nutrients and microbial activity, encourages the development of organic binding materials, and enhances the soil's porosity and aggregate content. However, the high porosity and hydrophobic functional groups of biochar may hinder water infiltration, thus reducing the effective porosity. Additionally, biochar particles can clog soil pores, affecting the soil's bulk density and water movement. An increased application of biochar may impede the diffusion of soil moisture, leading to uneven water distribution and reduced soil moisture content. The black surface of biochar can also decrease the soil's surface albedo, raise soil temperatures, and promote moisture evaporation, further affecting the soil's moisture levels. When applying biochar, one must consider its cumulative effects and regulate the application rate to avoid excessive changes in the moisture and other physical and chemical properties of the soil.

The improvement in the soil's EC following biochar application is closely related to the soluble salt ions that it contains [105]. The porous structure of biochar allows it to adsorb salts, increasing the soil's salinity and enhancing its EC. Moreover, by enhancing the soil's porosity and hydraulic conductivity, biochar can promote the leaching of soluble salts in saline–alkali soils, reducing the soil's EC values.

During the pyrolysis of base materials, some acidic functional groups experience hydrogen bond cleavage, typically rendering the biochar alkaline. Soluble salts are carried by biochar, and its ash, which contains various basic ions, can reduce the concentration of $H+$ ions in soil, significantly enhancing the levels of alkaline cations and increasing the soil's pH. Once incorporated into the soil, the biochar surface oxidizes, increasing the number of carboxyl groups and enhancing its negative charge. This negative charge can adsorb a certain quantity of exchangeable metal ions, which then bind with soluble organic compounds in the biochar, becoming fixed in the soil [106]. Consequently, the activity of these ions decreases, and the soil's pH increases. In saline–alkali soils, the effect of biochar on the soil's pH is mostly influenced by differences between the biochar's pH and that of the soil. Biochar can also lower the soil's pH by reducing the ESP in saline soils.

Biochar is primarily derived from agricultural and forestry waste and contains a certain amount of organic matter and nutrients. When applied to soil, it can increase the availability of these nutrients and enhance the activity of microorganisms that contribute to nutrient enrichment. Moreover, biochar possesses significant adsorption capacities and a well-developed porous structure, which reduce nutrient leaching and underground runoff, thereby maximizing the soil's nutrient retention. Biochar can also adsorb organic molecules from the soil, contributing to the formation of organic matter through continuous polymerization, and its stable carbon structure enhances its resistance to microbial degradation. Adsorptive properties stabilize unstable carbon in the soil and promote the formation of relatively stable organic matter, increasing SOC. Furthermore, by enhancing the stability of soil aggregates, biochar reinforces SOC's stability.

The surface functional groups of biochar can promote the binding of soil particles through hydrogen bonding and electrostatic interactions, enhancing the formation of aggregates. Additionally, the porous structure of biochar improves the water retention capacity of soil, thereby increasing the stability of aggregates under humid conditions. The application of biochar can also reduce soil compaction, increase porosity, and improve air circulation and water infiltration. At the same time, it provides a favorable habitat for soil microorganisms, promoting microbial biological activity. The bioproducts that are generated, such as polysaccharides and adhesives, also contribute to the stability of aggregates. The combination of biochar and soil organic matter can effectively promote the formation of more stable soil aggregates, thereby enhancing the soil's structural stability. This structural stability not only improves the soil's durability but also helps maintain its biodiversity and ecological functions, which is more conducive to the development of sustainable agriculture.

Biochar is rich in oxygen-containing functional groups on its surface (such as carboxyl and hydroxyl groups), which can provide negative charges and enhance the soil's ability to adsorb cations. Additionally, the application of biochar typically increases the soil's pH, thereby altering the charge distribution in the soil and further enhancing cation retention. Moreover, the interaction between organic matter and biochar can promote the formation of soil aggregates, thereby increasing the CEC. However, an excess of exchangeable calcium ions may bind with the organic matter in the soil to form aggregates, which can reduce the available exchange sites and decrease the CEC. Furthermore, in soils with high organic matter contents, the application of biochar might also trigger competitive adsorption phenomena, reducing the number of available surface sites for cation exchange and consequently lowering the soil's CEC.

Biochar demonstrates unique advantages in terms of cost-effectiveness and environmental impact. According to a study by Stegenta-Dąbrowska et al., biochar can significantly reduce carbon dioxide emissions during the composting process and increase the content of macronutrients in compost, thereby enhancing the quality of the compost [107]. Additionally, research by Fardin Sadegh-Zadeh et al. showed that the combined application of biochar and compost can significantly improve rice yields, indicating that biochar has a synergistic effect on enhancing the fertility of soil and the crop yield [17]. Although the initial production cost of biochar may be higher than that of traditional compost, its long-term environmental benefits, such as carbon sequestration and a reduction in greenhouse gas emissions, may make it a more sustainable option. In summary, these research findings indicate that biochar not only improves crop yields but also reduces greenhouse gas emissions and enhances the soil's carbon sequestration capacity, highlighting its significant potential in sustainable agricultural practices.

Biochar that is derived from agricultural and forestry waste can be applied to low-quality, degraded, and acidic soils, significantly increasing crop yields. Biochar application has considerable potential in agriculture and other fields. However, the way in which it improves the physicochemical properties of soil is influenced by factors such as the soil's texture, the biochar's characteristics, and environmental conditions. For instance, the excessive application of biochar may lead to a low bulk density and excessive porosity of the soil, hindering the ability of plant roots to absorb nutrients and water and intensifying the soil's microbial activity, thereby resulting in the overconsumption of soil organic matter. In addition, biochar is not entirely free of toxic substances. It contains certain quantities of polycyclic aromatic hydrocarbons, heavy metals, and phenolic compounds, and the concentrations of these substances may reach levels that threaten the health of the soil at increased application rates. Therefore, in specific applications, we should explore the interactions between different soil types and biochar application, focusing on the influence of the soil's texture on the efficacy of biochar amendments. The effects of biochar application under various climatic and experimental conditions must also be evaluated, and the optimal application rates should be identified to avoid issues of a low bulk density and excessive porosity through overuse, thereby ensuring a balance between microbial activity and organic matter in the soil. To achieve these goals, further research is required.

5. Conclusions

This study conducted a comprehensive bibliometric analysis of the literature on the effects of biochar, black carbon, and charcoal on soil's physicochemical properties from 2000 to 2023. The findings indicate that the role of biochar in soil improvement has garnered significant attention over the past two decades, with a rapid growth trend in related research. This trend reflects the increasing recognition within the academic community of biochar's potential role in agricultural sustainability and environmental protection.

Through a clustering analysis of the literature, this paper identified current research hotspots, including the effects of biochar application on soil's moisture retention, nutrient cycling, pH regulation, and other physicochemical parameters. Furthermore, this study highlights the increasingly interdisciplinary nature of biochar research, which spans multiple fields, such as agricultural science, environmental science, chemistry, and geography.

However, the current research predominantly focuses on laboratory conditions, with a lack of large-scale field trials and long-term field data. Future research needs to broaden the sample range and should also address the economic feasibility and operability of biochar in practical applications, particularly concerning the differences in effectiveness under various climatic and soil conditions.

Different sources of biochar have varying characteristics (such as porosity, specific surface area, pH, etc.), and different types of soil have different needs. We should select the appropriate biochar based on the soil type and crop requirements. It is also possible to mix biochar with other soil amendments to achieve optimal improvement effects. Additionally, monitoring the changes in the physical and chemical indicators of the soil is essential. Based on the data, adjustments to the application strategy should be made to maximize the advantages of biochar.

Biochar can improve the physicochemical properties of the majority of soils when used appropriately, but several aspects remain poorly understood. For instance, there is limited research on the enhancement of non-aqueous aggregate stability and particle density changes in soil, indicating a need for more data to understand biochar better. A deeper understanding of the changes in soil's physicochemical properties that are induced by biochar can be achieved by comparing the results from laboratory and pot experiments with field studies. This comparison will help elucidate the role of environmental factors in controlling changes in the physicochemical properties of soil that are induced by biochar.

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