Review

Biochar as a Climate-Smart Approach for Soil Health Improvement and Nano-/Microplastic Mitigation in Sustainable Agriculture: A Review

Anwar Abdelrahman Aly *

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Biochar as a Climate-Smart Approach for Soil Health Improvement and Nano-/Microplastic Mitigation in Sustainable Agriculture: A Review

Anwar Abdelrahman Aly

Soil and Water Science Department, Faculty of Agriculture, Alexandria University, Alexandria 21545, Egypt; aaaly@alexu.edu.eg; Tel.: +201152453435

Abstract

The increasing accumulation of nano-/microplastics (NMPs) in agricultural soils has become an emerging environmental concern, posing risks to soil health, crop productivity, and food safety. Due to their persistence and small size, NMPs can disrupt soil structure, alter microbial communities, and facilitate the transport and uptake of contaminants by plants. In this context, biochar has attracted significant attention as a climate-smart soil amendment capable of improving soil quality while mitigating emerging pollutants. This review explores the potential role of biochar, including modified biochar, as a sustainable strategy for enhancing soil health and reducing the risks associated with NMPs contamination in agricultural systems. The unique physicochemical properties of biochar—such as its high surface area, porous structure, and abundant functional groups—enable interactions with plastic particles and associated contaminants through adsorption, aggregation, and immobilization processes. These interactions can reduce mobility, bioavailability, and plant uptake of NMPs in soil. In addition, biochar contributes to soil fertility improvement by enhancing nutrient retention, increasing water holding capacity, improving soil structure, and stimulating beneficial microbial activity. Biochar application also plays an important role in climate change mitigation by stabilizing carbon in soils and reducing greenhouse gas emissions from agricultural systems. Although biochar is considered a promising material for sustainability, some types of biochar may have adverse effects in saline–alkaline soils due to their high pH and salinity, particularly when produced at high pyrolysis temperatures. Overall, integrating biochar or modified biochar into sustainable agricultural practices offers multiple co-benefits, including soil restoration, pollutant mitigation, improved soil health, and enhanced climate resilience. This review synthesizes recent advances in understanding the mechanisms by which biochar influences NMPs behavior in soil–plant systems and highlights current knowledge gaps and future research directions needed to support its effective application in sustainable agriculture.

Keywords: soil pollution; microplastics; nanoplastics; sustainable agriculture; carbon sequestration; soil–plant interactions; environmental remediation

1. Introduction

Agricultural soils are increasingly exposed to multiple environmental stresses, including climate change, soil degradation, and emerging contaminants such as nano-/microplastics (NMPs), which collectively threaten soil health, ecosystem functioning, and sustainable crop production [1–5]. Soil health refers to the capacity of soil to function as a living ecosystem that sustains plants, animals, and humans while maintaining environmental quality and supporting ecosystem services [6–8]. Maintaining soil health has become a central objective for sustainable agriculture and global food security [9] . However, intensive agricultural practices, excessive agrochemical inputs, and climate variability have accelerated soil degradation processes such as nutrient depletion, loss of organic matter, and reduced biological activity [10,11]. These challenges highlight the urgent need for innovative and climate-smart soil management strategies.

Climate change further exacerbates soil degradation and threatens agricultural productivity worldwide [12–15]. Rising temperatures, irregular precipitation patterns, and extreme weather events influence soil moisture regimes, microbial processes, and nutrient cycling [12,15,16]. Agriculture itself is also a significant contributor to greenhouse gas emissions, accounting for a substantial portion of global emissions through land use change, fertilizer application, and soil management practices [12,13]. Consequently, sustainable soil management practices that enhance carbon sequestration while improving soil fertility are increasingly recognized as essential components of climate-smart agriculture [13,17,18].

In recent years, the accumulation of NMPs in agricultural soil has emerged as an additional environmental concern. Microplastics originate from various sources, including plastic mulching films, wastewater irrigation, sewage sludge application, and the degradation of larger plastic residues. Once introduced into the soil, these particles can alter soil physical properties, disrupt microbial communities, and adversely affect plant growth as well as nutrient uptake [19–23]. Studies have shown that microplastics can interfere with soil aggregation and reduce soil stability, thereby threatening long-term soil productivity and ecosystem functioning [2,23–25]. In fact, the plastic production dramatically increased since the mid-20th century, and billions of tonnes generated globally with the extensive use of plastic mulch in agriculture [26–28]. A significant proportion of this material ultimately accumulates in soils, where it undergoes gradual degradation into microplastics (MPs, <5 mm) and nanoplastics (NPs, <1 μm) [29]. While MPs are widely detected across environmental compartments, the occurrence, behavior, and impacts of NPs remain poorly understood, largely due to limitations in current detection and quantification techniques [30]. NPs pose a particular concern in agricultural systems because of their small size and high mobility, which enables them to penetrate plant tissues and enter the food chain [16]. Unlike MPs, which are often restricted by root barriers, NPs can be taken up by plants and transported within vascular tissues [31]. Experimental evidence indicates that NP surface charge influences their interaction with root exudates and internal transport pathways [21,31–33]. Their accumulation in crops has been associated with adverse effects on plant productivity and grain quality, raising concerns about subsequent transfer to humans through food consumption [16]. Indeed, recent findings have confirmed the presence of plastic particles in various human tissues, highlighting potential health risks associated with long-term exposure [34–36] . Besides, MPs may act as carriers for other contaminants such as antibiotics, heavy metals, and pathogenic microorganisms, further complicating soil pollution dynamics [37]. Their persistence and small particle size allow them to interact with soil biota and potentially enter the food chain through plant uptake. Evidence indicates that MPs contamination can impair root development, reduce microbial diversity, and disturb rhizosphere processes, ultimately affecting crop productivity and environmental health [16,37].

Biochar has recently gained considerable attention as a promising climate-smart soil amendment capable of addressing several of these challenges simultaneously. Biochar is a carbon-rich material produced through the pyrolysis of biomass under limited oxygen conditions [38,39]. Due to its highly porous structure, large surface area, and functional groups, biochar can enhance soil physical, chemical, and biological properties [40–43]. Its application to soil has been widely reported to improve nutrient retention, increase cation exchange capacity, enhance soil water-holding capacity, and stimulate beneficial microbial activity [43–45]. In addition, biochar is considered a stable form of carbon that can remain in soil for hundreds to thousands of years, making it an effective tool for carbon sequestration and climate change mitigation [16,46]. Beyond improving soil fertility, biochar also shows significant potential for the remediation of emerging soil pollutants, including NMPs [47–49]. The sorptive properties of biochar enable it to interact with plastic particles and associated contaminants, thereby reducing their mobility and ecological risks [50]. Recent studies demonstrated that biochar amendments can alleviate the toxic effects on plants and soil microbial communities by

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enhancing antioxidant responses, improving nutrient metabolism, and restoring rhizosphere microbial diversity [16,34,37,51].

Additionally, experimental studies have indicated that biochar materials derived from agricultural residues can effectively remove NMPs from soils, with removal efficiencies exceeding 60–90% under certain conditions [16,48]. These findings suggest that biochar may serve as an effective tool for mitigating NMPs pollution in agroecosystems while simultaneously improving soil quality and crop productivity [16].

Given these multifunctional benefits, biochar represents a promising climate-smart strategy for sustainable agriculture. By improving soil health, enhancing resilience to climate stress, and mitigating the ecological impacts of NMPs contamination, biochar has the potential to contribute significantly to environmentally sustainable food production systems [16,47,52,53]. Nonetheless, the interactions between biochar and NPs in soil environments, and their implications for plant uptake, soil health, and crop nutrition, remain insufficiently explored. Further research is needed to optimize biochar characteristics and better understand its role in reducing NPs bioavailability in agricultural systems [40–42,52,54,55].

Therefore, this review aims to synthesize current knowledge on the role of biochar as a climate-smart soil amendment, focusing on its potential to improve soil health and mitigate nano-/microplastics pollution in agricultural systems. The review highlights the mechanisms through which biochar interacts with soil properties, microbial communities, and plastic contaminants, and discusses future research directions for integrating biochar into sustainable soil management practices.

2. Biochar as a Climate-Smart Agricultural Strategy

2.1. Biochar: Definition and Concept

Biochar is a carbon-rich material produced from biomass through pyrolysis under limited or no oxygen conditions. It has gained increasing attention as a sustainable soil amendment and a potential tool for climate change mitigation due to its high stability and multifunctional properties [56,57].

2.1.1. Properties of Biochar

Biochar is characterized by high porosity, large surface area, significant cation exchange capacity (CEC), and the presence of functional groups and essential nutrients such as nitrogen, phosphorus, and potassium [58]. These physicochemical properties enable biochar to improve soil conditions and nutrient dynamics [58].

Biochar electrical conductivity (EC) and pH are strongly influenced by both pyrolysis temperature and feedstock type [59] (Figures 1 and 2, and Table 1). Figure 1 shows that the average biochar pH, derived from various feedstocks, increased from 7.9 at a pyrolysis temperature of 400 °C to 10.1 at 800 °C. Similarly, Figure 2 indicates that the average biochar EC increased from 1.7 to 2.7 dS m^{-1} as the pyrolysis temperature rose from 400 °C to 800 °C [16,60–65].

In general, both parameters increase with rising pyrolysis temperature due to several concurrent processes: (i) formation of carbonate minerals, (ii) accumulation and concentration of alkaline ash and soluble salts (e.g., Ca, Mg, and K), and (iii) thermal decomposition and loss of acidic functional groups (e.g., –COOH). Overall, pyrolysis temperature and feedstock type play a critical role in determining biochar pH, EC, and other associated physicochemical properties [16,60–65].

Biochar application is particularly effective in acidic, non-saline soils, where it can increase soil pH and enhance nutrient availability. In contrast, its use in saline–sodic soils should be carefully managed, as the inherently high pH and soluble salt content of biochar may intensify salinity and sodicity constraints [39,42,66–72].

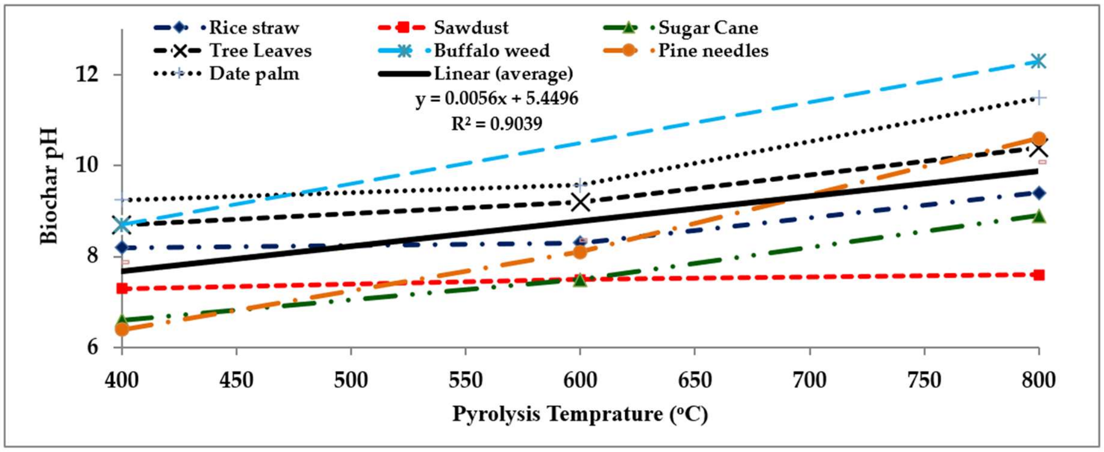

Figure 1. Relationship between pyrolysis temperature and biochar pH using different feedstocks [16,60–65].

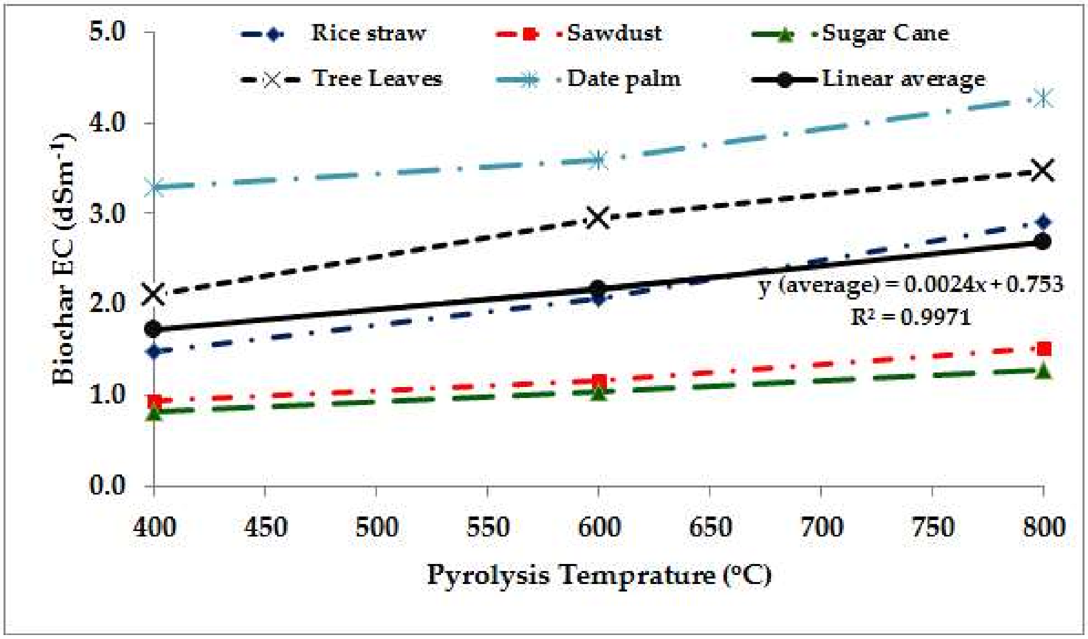

Figure 2. Relationship between pyrolysis temperature and biochar EC using different feedstocks [16,60–65].

2.1.2. Effects of Biochar on Soil Quality

The application of biochar has been widely reported to enhance soil physical, chemical, and biological properties. It improves soil structure, increases water-holding capacity, and enhances nutrient retention while stimulating beneficial microbial activity [56,59]. These improvements are particularly significant in degraded and sandy soils [73] (Figure 3).

2.1.3. Impact on Crop Productivity

Biochar applications can lead to increased crop yields, improved nutrient use efficiency, and reduced nutrient leaching losses [73]. However, the magnitude of these benefits varies depending on soil type, biochar characteristics, and application rates [59] (Figure 3).

2.1.4. Environmental Benefits

Biochar contributes to environmental sustainability by acting as a long-term carbon sink, thereby supporting climate change mitigation [57]. It also reduces greenhouse gas emissions from soil and immobilizes heavy metals and organic pollutants, improving environmental quality [59] (Figure 3).

2.1.5. Limitations and Risks

Despite its numerous benefits, biochar applications have several limitations. Its effectiveness can vary considerably depending on feedstock type and pyrolysis conditions, which influence its physicochemical properties and behavior in soil [74]. Moreover, due to its typical alkaline nature, biochar addition may increase soil pH beyond optimal levels, potentially affecting nutrient availability and crop performance [75] (Table 1). In addition, biochar may contain contaminants such as polycyclic aromatic hydrocarbons (PAHs), heavy metals, polychlorinated dibenzodioxins, polychlorinated dibenzofurans, and VOCs generated during pyrolysis, which can pose environmental and ecological risks [76]. Furthermore, long-term impacts on soil ecosystems remain uncertain and require further investigation [57] (Figure 3).

Table 1. Impact of pyrolysis temperature and biochar pH. [60–64].

Pyrolysis Temperature (°C)	pH	Type of biochar acidity
300-400 (Low)	~6–7	Slightly acidic to neutral
400-600 (Medium)	~7–9	Neutral to moderately alkaline
600-800 (High)	~9–11+	Strongly alkaline, especially for mineral-rich feedstocks

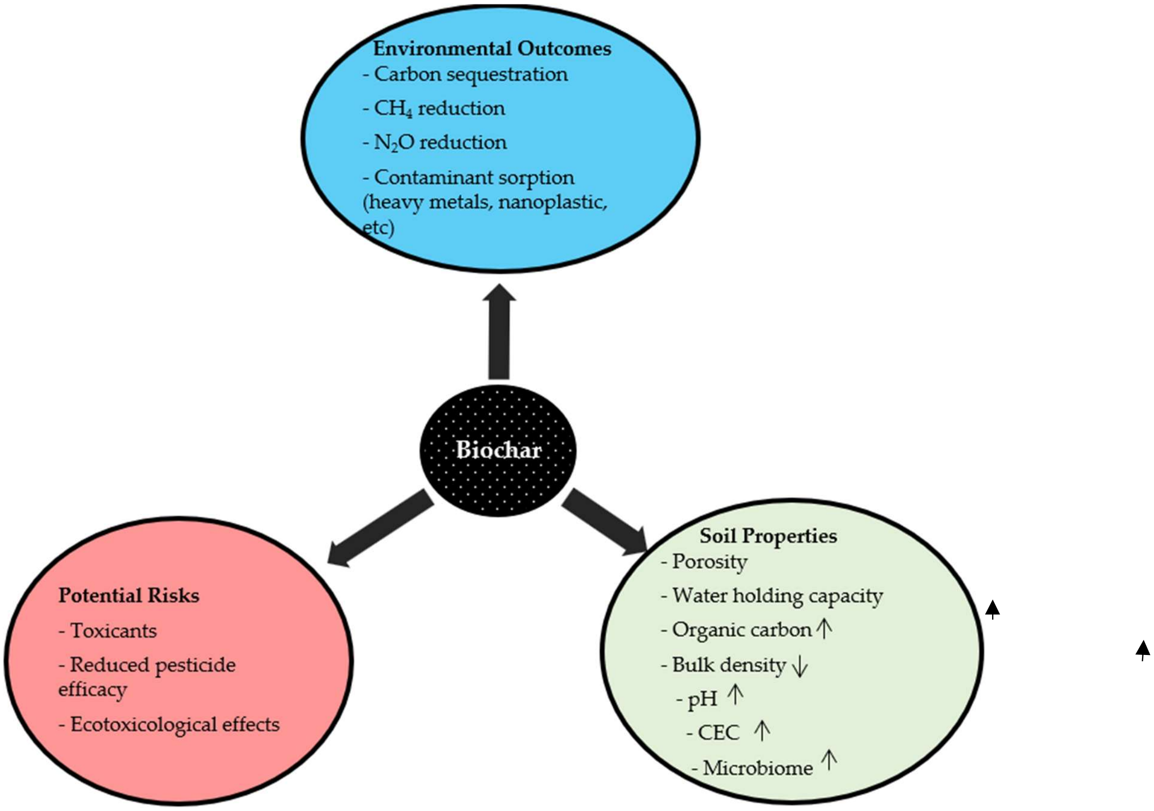

Figure 3. Biochar Effects Framework.

2.2. Climate-Smart Agriculture (CSA)

The CSA is an integrated approach to agricultural development that seeks to sustainably increase productivity, enhance resilience (adaptation) to climate change, and reduce or remove greenhouse gas emissions (mitigation), while supporting food security and livelihoods. This framework aligns agricultural practices with the dual challenges of climate change and sustainable development [77–79] (Figure 4).

In simple terms, climate-smart agriculture is built around three main objectives:

1. Increasing agricultural productivity through improved soil management practices, efficient water use, and sustainable intensification techniques that enhance crop yields without degrading natural resources [79] .

2. Enhancing resilience to climate change by strengthening the capacity of farming systems to cope with climate variability and extreme events (e.g., droughts and floods), including the adoption of climate-resilient crop varieties and adaptive management strategies [80,81].

3. Reducing greenhouse gas emissions by promoting low-emission technologies, improved nutrient management, and carbon sequestration practices, thereby contributing to climate change mitigation [77,78,80,82–85].

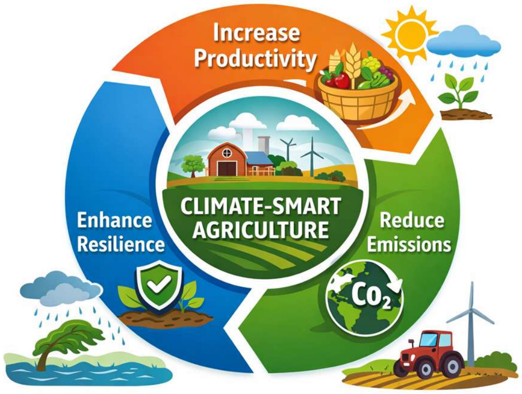

Figure 4. Goals of Climate-Smart Agricultural.

The biochar contributes to CSA goals through multiple pathways: i) Carbon sequestration: Biochar stores stable carbon in soils for long periods, acting as a persistent carbon sink and enhancing soil carbon storage [86]. ii) Reduced greenhouse gas emissions: Biochar amendments have been shown to reduce nitrous oxide (N_2O) emissions from soils and improve nitrogen use efficiency by regulating soil microbial processes and nutrient cycling [87]. iv) Circular bioeconomy: Biochar production converts agricultural and organic wastes into valuable soil amendments, promoting resource recycling and sustainable waste management while contributing to climate change mitigation [88].

3. Biochar and Nano -/ Microplastics (NMPs) Interaction

3.1. Definition and Sources of Micro- and Nanoplastics

Microplastics (MPs) are plastic particles smaller than 5 mm, while nanoplastics (NPs) are typically less than 1 μm and may originate from further degradation of MPs [89]. These particles arise from both primary sources (e.g., cosmetics, fibers) and secondary sources through fragmentation of larger plastics [90]. They are now widely distributed in aquatic and terrestrial environments and can enter soils via wastewater, sludge, and agricultural plastic residues [49]. NMPs have been reported to adversely affect several key soil functions and ecological processes. In terms of soil structure, microplastics reduce water-stable macro-aggregates and disrupt soil aggregation, thereby negatively affecting soil stability and porosity [20]. They also influence soil microbial communities by decreasing microbial biomass and altering community composition, including an estimated 10–15% decline in nitrogen-fixing bacteria populations [91]. Furthermore, microplastics interfere with nutrient cycling by reducing the availability of essential nutrients such as nitrogen and phosphorus and by affecting soil enzyme activities involved in nutrient transformation [16,92]. In addition, microplastics can act as carriers for environmental contaminants because of their strong adsorption capacity for heavy metals and pesticides, facilitating the transport and distribution of pollutants within soil systems [93] (Table 2).

Table 2. Impact of Microplastics on Soil Systems.

Impact Area	Observed Effect	Key Findings	Reference
Soil aggregation	Reduced macro-aggregates	Microplastics decrease water-stable soil aggregates and disrupt soil structure	De Souza Machado et al. [20]
Microbial activity	Decline in microbial diversity	Microplastics reduced microbial biomass and altered community structure; ~10–15% decline in N-fixing bacteria	Fei et al. [91]
Nutrient cycling	Reduced nutrient availability	Presence of microplastics decreased nitrogen and phosphorus availability and affected enzyme activity	Aly et al. [16]and Aralappanavar et al. [92]
Pollutant transport	Carrier for contaminants	Microplastics can absorb and transport heavy metals and pesticides, acting as vectors in soil	Menéndez-Pedriza et al.[93]

3.2. Biochar Properties Relevant to MNPs Interaction

Microplastics may inhibit root growth and disrupt plant metabolism [16]. However, biochar amendments have been shown to enhance root development, nutrient transport, and microbial activity in contaminated soils [16]. Biochar is a carbon-rich material characterized by a high surface area, porous structure, and abundant surface functional groups, making it an effective adsorbent for a wide range of environmental contaminants [94]. High-temperature biochar generally exhibits greater surface area, aromaticity, and hydrophobicity, which enhances its adsorption capacity for organic and inorganic pollutants [94].

3.3. Adsorption Mechanisms Between Biochar and NMPs

Biochar interacts with *NMPs* through multiple mechanisms [49,95–98]:

- Hydrophobic interactions.
- π–π stacking (aromatic interactions).
- Electrostatic attraction.
- Physical entrapment in pores.

These mechanisms often operate simultaneously and explain the high removal efficiency of biochar (>90% in many studies) [90]. Additionally, biochar’s porous “honeycomb” structure facilitates interception and filtration of MPs [99] (Table 3 and Figure 5).

Several studies have demonstrated the effectiveness of biochar in mitigating microplastic and nanoplastic contamination through different adsorption and immobilization mechanisms such as: wheat straw biochar produced at 500–700°C showed high efficiency in removing polystyrene microplastics, achieving more than 86% removal through adsorption processes involving surface functional groups and pore trapping mechanisms [48]. Similarly, cow dung biochar pyrolyzed within the same temperature range effectively removed polystyrene microplastics, with removal efficiencies reaching up to 92.4%, mainly due to surface adsorption mediated by functional groups such as COO^- and CO_3^{2-} [48]. Corn stover biochar produced at approximately 500°C demonstrated more than 95% immobilization of polyethylene microplastics through physical trapping and indirect enhancement of microbial activity in soil systems [100]. In addition, sawdust-derived biochar produced at 600°C was reported to remove polyethylene nanoplastics with efficiencies of up to 60%, primarily through hydrophobic interactions, π–π stacking between aromatic structures, and physical entrapment within the porous biochar matrix [16] (Table 3).

Table 3. Biochar Performance in NMPs Mitigation.

Biochar Feedstock	Pyrolysis Temp	Target Plastic	Mechanism	Efficiency	Reference
Wheat straw	500–700°C	Polystyrene MPs	Adsorption (surface functional groups, pore trapping)	>86% removal	Chai et al. [48]
Cow dung	500–700°C	Polystyrene MPs	Surface adsorption (functional groups COO^-, CO_3^{2-})	Up to 92.4% removal	Chai et al. [48]
Corn stover	~500°C	Polyethylene MPs	Physical trapping + indirect microbial activity improvement	>95% immobilization	Wang et al. [100]
Sawdust	600°C	Polyethylene NPs	Hydrophobic interactions, π–π stacking (aromatic interactions), Physical entrapment in pores	Up to 60% removal	Aly et al. [16]

3.4. Effects of Biochar on NMPs Mobility and Transport

Biochar can strongly influence the mobility, transport behavior, and environmental fate of NMPs in soil and water systems. In many cases, biochar acts as an immobilizing agent by adsorbing plastic particles onto its highly porous surface and reducing their movement through soil profiles. The porous structure, large specific surface area, and abundance of oxygen-containing functional groups (e.g., –OH, –COOH) promote electrostatic attraction, hydrophobic interactions, van der Waals forces, and pore entrapment between biochar and NMPs [16,48,101]. These interactions decrease the leaching potential of NMPs and limit their migration into groundwater systems. In addition, biochar can improve soil aggregation and increase soil water retention, which further stabilizes plastic particles within soil matrices and reduces transport during irrigation or rainfall events [39,48,64].

Biochar amendments may also indirectly reduce NMPs mobility by stimulating microbial activity and enhancing the formation of soil aggregates. Improved microbial biomass and extracellular polymeric substances (EPS) can bind soil particles and trap microplastics within aggregate structures [37,92]. Furthermore, aged or oxidized biochar surfaces often possess greater surface reactivity, enhancing the retention of NPs through stronger adsorption mechanisms [20,50,102].

On the other hand, the influence of biochar is not always strictly immobilizing. Under certain environmental conditions, especially in sandy soils or highly saturated systems, fine biochar particles may act as mobile colloids and facilitate the transport of NPs through soil pores [103–105]. This phenomenon, known as colloid-facilitated transport, occurs when NPs attach to suspended biochar particles that remain mobile in water flow pathways [103–105]. The risk is generally higher for smaller NPs because of their lower settling tendency and higher colloidal stability. Transport behavior can also be influenced by pH, ionic strength, dissolved organic matter, and the surface charge of both biochar and plastic particles [103–105].

The pyrolysis temperature and feedstock type of biochar further determine its impact on NMPs mobility. High temperature biochar generally possess larger surface areas, higher aromaticity, and stronger hydrophobicity, which improve adsorption and immobilization efficiency. Conversely, low temperature biochar may contain more dissolved organic carbon and smaller particles that could enhance colloidal transport under some conditions. Therefore, the overall effect of biochar on NMPs transport depends on multiple interacting factors, including soil texture, water flow conditions, particle size of NMPs, biochar aging status, and biochar physicochemical properties [48,64,106] (Figure 5). NMPs can adsorb and transport various environmental pollutants, including heavy metals, pesticides, antibiotics, and hydrophobic organic compounds, thereby acting as vectors for contaminant migration in soil and aquatic systems [32,103,106–110]. Biochar can mitigate these risks through multiple mechanisms. Due to its high surface area, porous structure, and abundant functional groups, biochar may compete with NMPs for pollutant adsorption, thereby reducing contaminant loading on plastic surfaces. In addition, biochar can simultaneously immobilize both microplastics and associated contaminants through adsorption, pore entrapment, electrostatic interactions, and surface complexation. This dual function highlights the potential of biochar as an effective amendment for the integrated remediation of co-existing plastic and chemical pollution in contaminated environments [64,106].

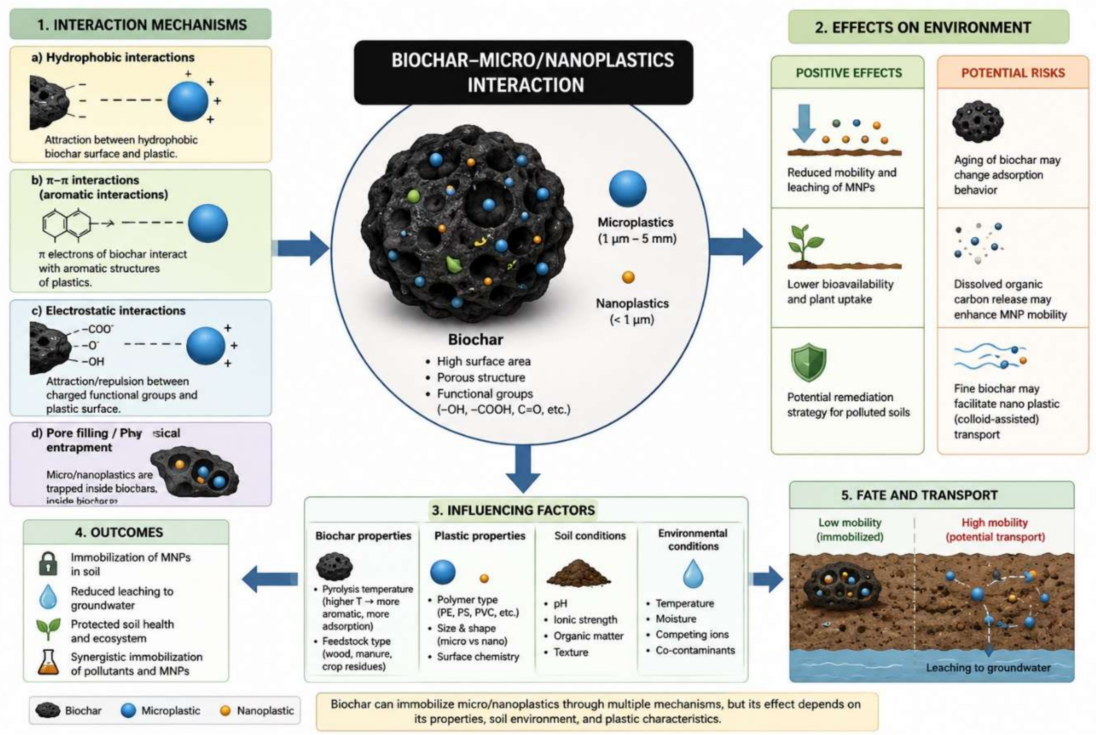

Figure 5. Biochar NMPs interaction.

4. Research Gaps and Future Perspectives

Despite the increasing number of studies investigating the interactions between biochar and micro-/nanoplastics (NMPs), several important research gaps remain unresolved. One major limitation is the insufficient understanding of NPs behavior in soil and aquatic environments. Compared with microplastics, NPs possess much smaller particle sizes, larger surface-area-to-volume ratios, and higher colloidal mobility, which can significantly alter their transport, toxicity, and interactions with soil minerals, microorganisms, and plant roots. However, reliable methods for detecting, quantifying, and characterizing NPs in complex environmental matrices are still limited, resulting in considerable uncertainty regarding their environmental fate and ecological risks [111,112].

Another critical gap is the lack of field-scale validation of laboratory findings. Most current studies on biochar–NMPs interactions are conducted under controlled laboratory or short-term greenhouse conditions, which may not accurately represent real agricultural systems. Environmental factors such as rainfall variability, irrigation practices, temperature fluctuations, soil heterogeneity, and natural organic matter can substantially influence the behavior of both biochar and plastic particles under field conditions. Therefore, long-term field experiments are needed to evaluate the practical effectiveness, persistence, and environmental safety of biochar applications for NMPs mitigation in different soil types and climatic regions [2,113].

There is also insufficient knowledge regarding the long-term stability of biochar–NMPs interactions. Biochar undergoes physical, chemical, and biological aging after soil application, which can alter its surface chemistry, porosity, functional groups, and adsorption capacity over time. Aging processes may either strengthen or weaken the retention of MPs and NPs, potentially affecting their remobilization under changing environmental conditions. In addition, the degradation products generated from aged plastics and aged biochar interactions remain poorly understood, particularly concerning their impacts on soil microbial communities and nutrient cycling [114,115].

Furthermore, future studies should focus on combined contamination systems rather than investigating NMPs as isolated pollutants. In natural environments, microplastics frequently coexist with heavy metals, pesticides, antibiotics, petroleum hydrocarbons, and other emerging contaminants. These co-contaminants may compete for adsorption sites, alter pollutant bioavailability, or produce synergistic toxic effects. Understanding how biochar simultaneously interacts with plastics and multiple contaminants is essential for designing integrated remediation strategies and evaluating potential environmental trade-offs [103,116,117].

Additional research is also needed to optimize biochar properties for NMPs remediation. Feedstock type, pyrolysis temperature, particle size, and surface modification strongly influence adsorption efficiency and environmental performance. However, standardized protocols for selecting or engineering biochar specifically for MPs and NPs remediation are still lacking. Moreover, economic feasibility, large-scale production, and potential unintended impacts of biochar application require further assessment before widespread agricultural implementation can be recommended [39,64].

5. Conclusions

Nano-/ microplastic contamination has become a growing threat to soil health and sustainable agriculture. These plastic particles originate from multiple agricultural and environmental sources, including plastic mulching, wastewater irrigation, sewage sludge application, and atmospheric deposition. Biochar offers a promising climate-smart solution for addressing this challenge due to its ability to improve soil properties, enhance microbial activity, and immobilize plastic pollutants. The adsorption capacity, porous structure, and functional groups of biochar make it an effective material for mitigating microplastic contamination in soils while simultaneously enhancing soil fertility and carbon sequestration. Integrating biochar into sustainable agricultural practices may therefore contribute to improved soil health, reduced environmental pollution, and climate change mitigation. In Fact, biochar is a promising material for mitigating micro- and nanoplastic pollution due to its strong adsorption capacity and ability to modify soil properties. However, its effectiveness depends on environmental conditions, and further field-based studies are required to fully validate its application.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

NMPs	nano-/microplastics
MPs	microplastics
NPs	nanoplastics
CSA	Climate-smart agriculture

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