

Review

A Review of Biochar-Industrial Waste Composites for Sustainable Soil Amendment: Mechanisms and Perspectives

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Abstract

Soil acidification, salinization, and heavy metal pollution pose serious threats to global food security and sustainable agricultural development. Biochar, with its high porosity, large surface area, and abundant functional groups, can effectively improve soil properties. However, due to variations in feedstocks and pyrolysis conditions, it may contain potentially harmful substances. Industrial wastes such as fly ash, steel slag, red mud, and phosphogypsum are rich in minerals and show potential for soil improvement, but direct application may pose environmental risks. The co-application of biochar with these wastes can produce composite amendments that enhance pH buffering capacity, nutrient availability, and pollutant immobilization. Therefore, a review of biochar-industrial waste composites as soil amendments is crucial for addressing soil degradation and promoting resource utilization of wastes. In this study, the literature was retrieved from Web of Science, Scopus, and Google Scholar using keywords including biochar, fly ash, steel slag, red mud, phosphogypsum, combined application, and soil amendment. A total of 144 articles from 2000 to 2025 were analyzed. This review summarizes the physicochemical properties of biochar and representative industrial wastes, including pH, electrical conductivity, surface area, and elemental composition. It examines their synergistic mechanisms in reducing heavy metal release through adsorption, complexation, and ion exchange. Furthermore, it evaluates the effects of these composites on soil health and crop productivity, showing improvements in soil structure, nutrient balance, enzyme activity, and metal immobilization. Finally, it identifies knowledge gaps as well as future prospects and recommends long-term field trials and digital agriculture technologies to support the sustainable application of these composites in soil management.

Keywords: biochar; industrial waste; synergistic effects; soil amendment; crop yield

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1. Introduction

Soil, composed of mineral particles, organic matter, water, air, and diverse communities of microorganisms and fauna, serves as a critical foundation for terrestrial ecosystem functioning, playing a key role in supporting crop growth, sustaining agricultural productivity, and regulating environmental quality [1]. However, in recent years, global soil quality has been declining due to unsustainable farming practices, industrial pollution, and land overexploitation. Problems such as acidification, salinization, organic contamination, heavy metal accumulation, and fertility degradation have become increasingly

prominent [2]. These adverse changes severely constrain arable land productivity and pose significant threats to global food security and ecological stability [3].

To address soil degradation, the design of efficient, low-cost, and environmentally friendly soil amendments has become a critical area of research [4]. Biochar, a carbon-rich substance derived from the pyrolysis of biomass under a limited oxygen supply, has attracted considerable attention due to its high surface area, abundant functional groups, and excellent chemical stability [3]. These properties enable biochar to enhance soil structure, buffer pH, retain nutrients, and immobilize heavy metals [5–7]. Nevertheless, biochar derived from certain organic wastes such as sewage sludge or animal manure may contain harmful substances, including heavy metals and organic pollutants, posing potential environmental risks when applied to soil [8,9]. The performance of pristine biochar can be limited by its relatively low mineral content and surface reactivity, especially under complex soil conditions [10]. To overcome these limitations and improve the multifunctionality of biochar, mineral-rich additives have been increasingly integrated into biochar production and modification strategies.

Industrial solid wastes such as fly ash, red mud, steel slag, and phosphogypsum are generated in large quantities and are rich in nutrient elements, metal salts, and reactive mineral phases, making them potentially valuable resources for agricultural soil improvement [11–14]. However, their direct application to soil may lead to environmental risks such as heavy metal leaching and poor stability [15,16]. To mitigate these issues and enhance their agronomic benefits, their co-utilization with biochar has emerged as a promising strategy. Biochar can stabilize the toxic elements in industrial wastes, while the mineral components of these wastes can improve the properties of biochar, offering synergistic effects in soil pH buffering, nutrient supply, and heavy metal immobilization [17]. For example, the incorporation of red mud can significantly increase the sorption capacity of biochar for heavy metals [18], while phosphogypsum helps to neutralize its alkalinity and supplement essential nutrients [19]. Therefore, the combined use of industrial wastes and biochar is considered an effective way to improve both environmental safety and soil amendment efficacy.

Recently, growing attention has been paid to the benefits of biochar and its co-application with typical industrial wastes on agricultural soil improvement. However, systematic reviews focusing on their synergistic mechanisms, agronomic benefits, application potential, and existing challenges remain limited. Therefore, this review aims to fill this knowledge gap by systematically summarizing the recent progress in the co-application of biochar and typical industrial wastes (e.g., fly ash, steel slag, red mud, and phosphogypsum) for soil amendment, thereby promoting the development and application of safe and efficient composite soil amendments. A targeted literature search was conducted using Web of Science, Scopus, and Google Scholar to collect peer-reviewed studies published between 2000 and 2025. Keywords such as “biochar,” “fly ash,” “steel slag,” “red mud,” “phosphogypsum,” “combined application,” “soil amendment,” “soil remediation,” “soil improvement,” “soil conditioner,” “soil application,” and “agricultural soil” were used to identify relevant publications. In total, 144 peer-reviewed articles were selected and critically reviewed to ensure a comprehensive and up-to-date coverage of the topic.

Based on the collected literature, this review focuses on the fundamental properties of raw materials, their composite mechanisms, and their impacts on soil physicochemical characteristics and crop performance. Moreover, it highlights key challenges and future research directions, providing theoretical insights and practical guidance for the application of biochar-industrial waste composites in agricultural soil management.

2. Properties, Impacts, and Limitations of Biochar in Agricultural Soils

Biochar is a carbon-rich solid material obtained through the pyrolysis of biomass under oxygen-limited conditions, with a variety of raw materials including agricultural and forestry residues (e.g., straw, sawdust), domestic wastes (e.g., manure, eggshells), and industrial wastes (e.g., sewage sludge) [5]. Due to its unique physicochemical properties such as a large specific surface area (SSA), a developed pore structure, abundant surface functional groups, and a high carbon content, biochar has been widely studied for applications in soil amendment, greenhouse gas mitigation, and carbon sequestration [20–22].

In agricultural soils, biochar presents several potential advantages. It can increase the soil cation exchange capacity (CEC), thereby improving the retention of nutrients such as K^+ , Ca^{2+} , and Mg^{2+} , as well as facilitating the slow release of micronutrients, ultimately enhancing crop yield and quality [23]. The porous structure and oxygen-containing functional groups on the biochar surface confer strong adsorption capacities for heavy metals and organic pollutants, effectively reducing their bioavailability and mobility in soils [24]. Moreover, the porous and stable structure of biochar provides ecological niches for beneficial microorganisms, supporting microbial diversity and enhancing soil biological activity [25]. Biochar also exhibits weak alkalinity, which helps neutralize acidic soils, elevate pH, and improve nutrient accessibility in the rhizosphere [26].

2.1. Properties of Biochar

The physicochemical properties of biochar, including its elemental composition, pH, pore structure, specific surface area, cation exchange capacity, and types and abundance of surface functional groups, are largely influenced by the feedstock type and pyrolysis conditions [27,28]. Biochar is composed of both ash components (e.g., K, Ca, Na, Mg, and other inorganic minerals) and carbonaceous components (e.g., C, H, O, N, and nutrient elements), and the proportions of these components vary significantly depending on the feedstock. For instance, biochar derived from sugarcane bagasse contains significantly higher Si compared to that from tree bark, whereas the latter is richer in inorganic elements such as Ca, Al, and K [29]. Generally, biochars produced from plant-based materials (e.g., straw, wood chips) are characterized by lower ash and volatile matter contents, and due to their high cellulose and lignin contents, they tend to develop well-structured micropores and exhibit higher specific surface areas [27]. In contrast, biochars derived from manure or sludge typically contain higher ash and mineral contents, resulting in significantly higher pH and CEC values than those derived from plant-based materials [30]. The feedstock composition also influences the ionic composition of biochar. For example, manure-derived biochar is typically rich in Na and Mg, while straw-derived biochar often has a higher K content [28], which affects ion exchange and nutrient release behaviors when applied to soils.

Pyrolysis is a complex thermochemical conversion process involving the decomposition of organic macromolecules, the formation and loss of surface functional groups, and the enrichment and transformation of inorganic minerals, all of which significantly impact the properties of biochar [31]. Pyrolysis temperature has a notable effect on the pore structure and specific surface area of biochar. Generally, as the temperature increases, the release of volatile matter enhances pore formation and increases the SSA [32]. A higher SSA and uniform porous structure contribute to an improved water-holding capacity (WHC), thereby enhancing the soil's moisture retention and physical structure [33]. At lower pyrolysis temperatures (200–400 °C), biochar retains a higher content of oxygen-containing functional groups such as carboxyl, hydroxyl, carbonyl, phenolic hydroxyl, and aldehyde groups. These groups not only enhance the sorption of heavy metal ions and the immobilization of inorganic contaminants but also facilitate nutrient exchange and accumulation in soils [34].

However, at higher temperatures (400–500 °C or above), processes such as the dehydration and polycondensation of aliphatic hydrocarbons, the removal of polar functional groups, and dehydrogenation lead to a more aromatic and stable biochar structure [35]. This transformation is typically accompanied by a decline in surface functional group abundance and the CEC, thereby reducing the capacity of biochar to regulate nutrient and heavy metal availability through adsorption–desorption mechanisms. In addition, the pH of biochar generally ranges from neutral to alkaline and increases with rising pyrolysis temperature. This is attributed to the thermal decomposition of acidic oxygen-containing groups and the accumulation of basic mineral components (e.g., alkali and alkaline earth metal oxides), which enhance the alkalinity of the resulting biochar [36]. Overall, the physicochemical properties of biochar are shown in Figure 1 [37].

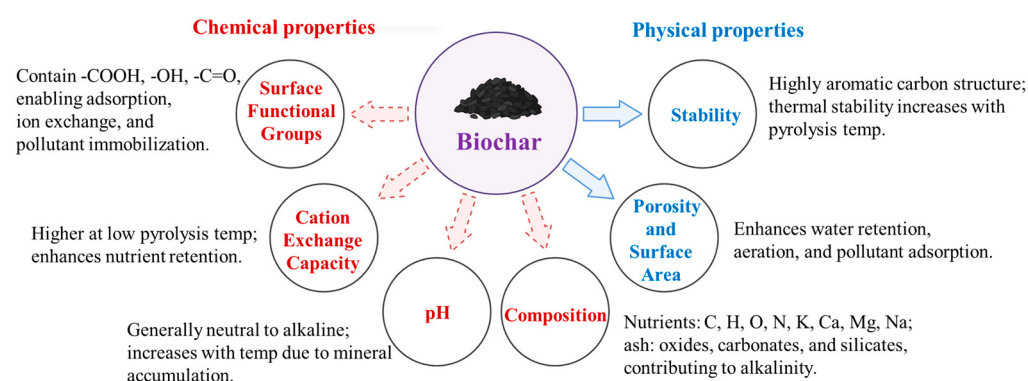


Figure 1. Physicochemical Properties of Biochar.

2.2. Effects of Biochar on Soil Properties and Plant Growth

The application of biochar to soil can improve the soil's physical properties, including its bulk weight, aggregate structure, porosity, and water holding capacity (WHC), as well as the soil's chemical properties including its pH value and cation exchange capacity (CEC) [38]. Due to its loose and porous structure, biochar has a much lower bulk density than soil, thus contributing to improved aeration and water infiltration when applied to soil [39]. The presence of oxygen-containing acidic groups (e.g., carboxyl and hydroxyl) enhances the negative surface charge of biochar, increasing its adsorption potential and WHC [40]. The large specific surface area and negative charge also promote higher soil CEC and the formation of stable aggregates [41,42]. For example, in Sri Lanka, Gamage et al. found that 1% rice husk biochar significantly improved sandy soil, raising its pH from 4.53 to 5.12 and its organic carbon from 0.86% to 1.23%, as well as increasing its CEC by 31% while decreasing its bulk density from 1.48 to 1.27 g·cm⁻³ [43]. In addition to carbon, biochar also contains nutrients such as N, P, and K, enhancing soil fertility and plant growth [44]. For instance, Sun et al. observed that straw biochar increased soil organic matter, the available P, alkali-hydrolyzed N, and the available K by 3.3–4.7%, 11.1–32.8%, 0.5–4.7%, and 26.7–35.6%, respectively, while reducing bulk density by 3.5–6.3% and increasing pH by 1.8–3.0% [45]. Pandit et al. showed that weed-derived biochar improved the acidic silt soil pH, WHC, and CEC, and increased the available P and K, leading to enhanced maize yields [46].

Moreover, base cations like Na⁺, K⁺, Ca²⁺, and Mg²⁺ that are present on the biochar surface can be exchanged with H⁺ and Al³⁺ in soil, increasing the saturation of exchangeable bases, thereby raising soil pH, improving nutrient availability, and reducing aluminum toxicity [47,48]. Due to the presence of alkaline oxides, carbonates, silicates, and various functional groups in biochar, Al³⁺ can be transformed into its less toxic form Al(OH)₃ through precipitation reactions or form complexes via specific adsorption [49], thus mitigating phytotoxicity. The mechanism of biochar in improving soil is shown in Figure 2 [2]. In

addition, the diverse microbial communities in soil can be reshaped by biochar application through improvements in the soil's physical and chemical conditions, ultimately enhancing soil fertility and crop productivity [50]. For instance, rice straw-derived biochar contains an abundance of labile carbon, which significantly promotes microbial activity and contributes to the restoration of biological fertility in degraded soils [51]. A field study conducted by Yamato et al. in South Sumatra, Indonesia, showed that applying $37 \text{ t} \cdot \text{ha}^{-1}$ of bark biochar to soil improved the soil's chemical properties, provided a favorable environment for root development, and promoted the proliferation of arbuscular mycorrhizal fungi, as well as the growth of maize, peanuts, and mango trees [52].

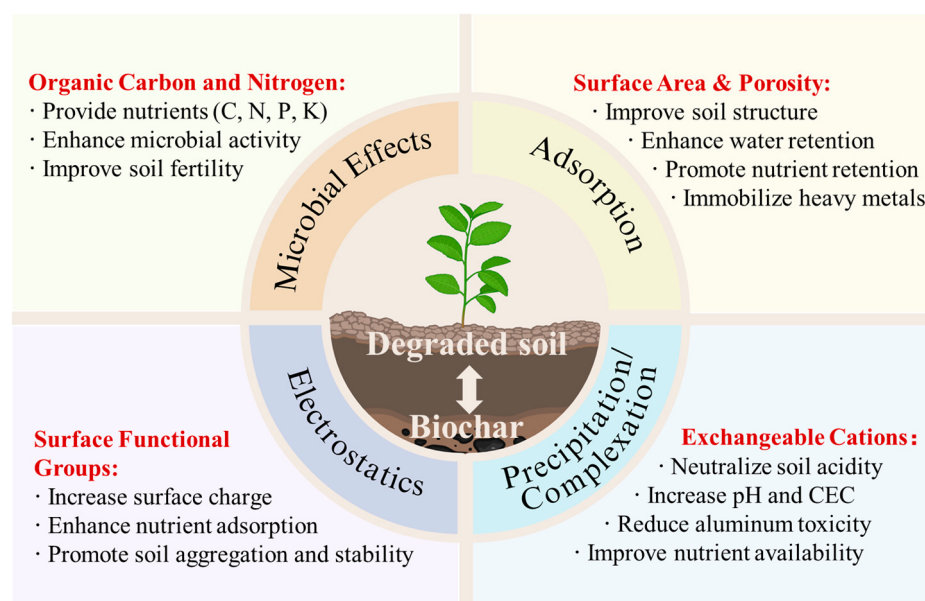


Figure 2. Mechanisms of Biochar in Soil Amendment.

In arid farmland, the application of biochar as a soil amendment has also demonstrated promising results. Pradhan et al. applied food waste-derived biochar to water-scarce green fodder farms in Qatar, integrating digital agricultural tools—the Analytic Hierarchy Process (AHP) and Geographic Information System (GIS)—to identify the optimal biochar feedstock and application rate. The results revealed that, through screening and optimization using AHP decision-making and GIS mapping, 2% biochar derived from mixed vegetable waste and pistachio shells exhibited a superior water retention performance, retaining 20% more water compared with the control group [53]. Artificial intelligence (AI) has also demonstrated great potential in supporting the application of biochar for soil improvement. Liew et al. developed a feedforward neural network to predict key pyrolysis-derived properties (O/C, H/C ratios, surface area), aiding the assessment of biochar stability and its water and nutrient retention capacity [54]. For Pb-contaminated soils, Cho et al. developed an AI-based predictive framework using machine learning to evaluate and optimize the long-term immobilization effects of various biochars. Applying 2.5% oilseed rape straw biochar, pyrolyzed at 700°C , significantly increased soil pH, CEC, and organic matters while notably reducing exchangeable Pb levels, showing a strong remediation performance [55].

2.3. Potential Risks and Limitations of Biochar

While biochar has shown considerable promise for soil improvement and environmental remediation, it still exhibits several limitations, such as a variability in biochar quality, the potential presence of contaminants, a limited nutrient content, uncertainties regarding its long-term effects, and a soil type dependency. The structural and chemical characteristics

of biochar, including its pore architecture, surface reactivity, and elemental makeup, are strongly influenced by the type of raw materials used and pyrolysis parameters, resulting in notable variabilities in its surface area, pH, and functional groups [56]. These variations result in different biochars having varying effects on different soil types, making it difficult to standardize its application across diverse agricultural systems [57].

Certain biochars, especially those produced from contaminated feedstocks like sewage sludge and animal manure, may contain harmful substances including heavy metals, especially Pb, Cd, Cu, and Zn, PAHs, pathogens, and antibiotics [58,59]. For example, the addition of sewage sludge biochar to soil decreased the availability of As, Cr, Co, Ni, and Pb owing to interactions with its surface functional groups, but improved the availability of Cd, Cu, and Zn due to its own heavy metal content, thus posing a threat to soil quality and crop health [60]. Consequently, the biochars produced from such feedstocks require thorough testing and quality control to ensure their safety for agricultural applications. However, compared to biochars from grasses or wood, sewage sludge biochar and animal manure biochar typically contain higher levels of N and P [61]. Generally, plant-based biochars have lower nutrient content, and applying such biochar to nutrient-poor soils can lead to a decrease in the bioavailability of N and P [62]. Therefore, co-application with other fertilizers is often required to meet the nutrient demands of crops.

Most current studies focus on the short-term effects of biochar on soil improvement. As the application time of biochar in soil increases, the structure, surface properties, and organic matter of the biochar undergo changes, which affect its long-term effectiveness. As reported by Mia et al., biochar aging leads to increased surface oxidation and changes in the physicochemical properties of the biochar, such as enhanced surface negativity and a greater ion exchange capacity. These shifts promote the association of organic substances with minerals, and reduce the affinity for organic contaminants [63]. Biochar can also alter the abundance, activity, and community structure of soil microorganisms. However, its long-term effects on soil microbial communities vary greatly across different land-use types, such as forests and croplands. In forest soils, the decline in the abundance of Gram-positive and general bacteria is more significant. The interaction between the effects of charcoal biochar and soil conditions complicates the soil amendment outcomes [64].

The performance of biochar is closely influenced by the properties of the target soil. In soils that are acidic, depleted, or structurally degraded, biochar often enhances the soils' physical condition, moisture retention, and nutrient dynamics to a notable extent [49]. However, in fertile or alkaline soils, the effects of biochar may be limited and could even have negative impacts. Novak et al. found that applying alkaline poultry litter biochar raised the soil's pH above 8.0, resulting in a decline in nutrient availability for plants [65]. Therefore, biochar application should be precisely adjusted according to specific soil types and regional conditions. Combining biochar with different types of industrial waste is a promising method to overcome its limitations and broaden its range of applications [66].

3. Utilization of Industrial Wastes in Agricultural Soils

With the rapid acceleration of industrialization, the generation of industrial solid waste has been steadily increasing. This waste encompasses a wide range of slags, dusts, and other particulate residues discharged into the environment and are generally classified into general and hazardous solid wastes. General solid waste, which constitute the majority of industrial by-products, include tailings, fly ash, coal gangue, smelting slag, steel slag, furnace slag, red mud, and phosphogypsum [67,68]. Due to their complex composition, the long-term stockpiling of these materials poses serious threats to the surrounding soils, water bodies, and atmospheric systems. Consequently, increasing attention has been paid

to the resource-oriented utilization of industrial solid waste to mitigate environmental burdens and enhance their application value.

In recent years, researchers have focused on incorporating industrial solid waste with a high production volume, relatively stable composition, and strong soil amelioration potential into agricultural soil management systems. Among these, fly ash (FA), steel slag (SS), red mud (RM), and phosphogypsum (PG) have emerged as prominent candidates due to their unique properties. The following sections provide a comprehensive review of these materials, with emphasis on their physicochemical characteristics, effects on soil properties and plant growth, and potential environmental risks.

3.1. Fly Ash

3.1.1. Composition and Properties

Fly ash (FA) is a fine particulate by-product generated during coal combustion in thermal power plants. It is characterized by good flowability and typically consists of the oxides of aluminum (Al_2O_3), iron (Fe_2O_3), calcium (CaO), silicon (SiO_2), and unburned carbon (C) [69]. In China, annual FA emissions have approached 780 million tons, with nearly 200 million tons remaining underutilized and over 3 billion tons cumulatively stockpiled, posing significant threats to land resources and air quality [70]. FA possesses a low bulk density, a high WHC, and an alkaline pH, making it a promising amendment for acidic soils [16]. Furthermore, its large specific surface area and high porosity, combined with its alkaline nature and oxide-rich composition, facilitate its use in the immobilization of heavy metals in contaminated soils [71]. However, the presence of hazardous elements, like As, Pb, Cd, and Zn in some FA types, may pose environmental risks, thereby limiting its widespread application [72].

3.1.2. Effects on Soil Properties and Plant Growth

FA has been widely recognized as a cost-effective soil improvement and fertilizer supplement with agronomic and environmental benefits. For instance, Deepali et al. conducted a field trial in India and found that applying FA at rates of 0–50% improved the soil's porosity, pH, EC, CEC, WHC, and availability of P, K, Mg, Zn, and Mn. Optimal potato growth, biomass, and biochemical parameters were observed at 15% to 25% of FA application, indicating the potential of FA to enhance soil fertility and crop performance [73]. Similarly, Lee et al. confirmed that FA application increased the pH of sandy loam as well as silt soils and enhanced the uptake of Si, P, and K by rice, highlighting its suitability as an inorganic amendment for nutrient balancing in paddy fields [74]. Kumar et al. reported that acidic FA (pH = 5.89) improved water permeability and water retention as well as reduced soil bulk density in saline soils, and, at 4.5% application, significantly boosted straw and grain yield in wheat [75]. The application of FA can also remediate heavy metal-contaminated soils. Hu et al. employed NaOH-modified fly ash to treat soils contaminated with Cd, Cu, and Pb, and reported that the addition of 4% of modified fly ash reduced the concentrations of Cd, Cu, and Pb by 47.6%, 48.09%, and 62.73%, respectively. In addition, the treatment enhanced soil enzyme activities, including urease and alkaline phosphatase, thereby improving soil health [76].

3.1.3. Potential Environmental Risks

Although the use of FA in agriculture presents opportunities for resource recovery, its unmodified or excessive application also raises concerns over environmental and human health risks. For example, Xu et al. simulated accelerated carbonation scenarios and observed significantly increased leachings of Zn and Cd after carbonation. Under a single-layer liner system, the concentrations of Pb, Zn, and Cd exceeded the Class III limit of

groundwater quality standards (GB/T 14848-2017 [77]), with Cd consistently surpassing acceptable exposure thresholds, indicating potential pollution risks [78].

3.2. Steel Slag

3.2.1. Composition and Properties

Steel slag (SS) is a molten material formed during steel production, generated from molten residues in electric arc furnaces or basic oxygen furnaces [79]. The global annual production of SS is estimated at approximately 190 to 280 million tons [80]. Its primary chemical components include the oxides of Ca, Si, Fe, Mg, Al, Mn, and P, with calcium oxide (CaO) comprising 40–60 wt% and silicon dioxide (SiO₂) accounting for 13–20 wt%. The high CaO content confers a strong alkalinity to SS, allowing it to serve as an effective substitute for lime in the amelioration of acidic soils [81]. Additionally, active oxides in SS can react with heavy metal ions in soils through precipitation, complexation, or adsorption mechanisms, thereby reducing their mobility and bioavailability. These characteristics highlight the potential of SS as an effective amendment for treating soils contaminated with heavy metals [80].

3.2.2. Effects on Soil Properties and Plant Growth

SS that is rich in P, Fe, Ca, Mg, S, and Si serves as a nutrient source for infertile soils. Das et al. demonstrated that applying 2 Mg·ha⁻¹ of SS significantly increased the pH, SOC, available P, soluble Si, and exchangeable Ca²⁺ and Mg²⁺ in soil, thereby enhancing rice photosynthesis, nutrient uptake (N, P, Si), root and straw biomass, and grain yield [82]. Additionally, Xu et al. proposed a synergistic use of SS for CO₂ sequestration and Pb remediation. Incorporating 10% of SS with CO₂ curing achieved a 21.1% CO₂ capture rate, reduced Pb leaching concentrations to 4.6–8.6 µg/L and increased soil compressive strength to 292–407 kPa, over ten times that of untreated soil [83]. SS may also replace natural lime as a soil conditioner, reducing the environmental impacts associated with limestone mining. As an alkaline waste, SS can improve the pH of acidic soils. As shown in Figure 3, the application of SS to soil can provide nutrients, reduce heavy metal leaching, enhance CO₂ sequestration, and increase the soil's pH [84].

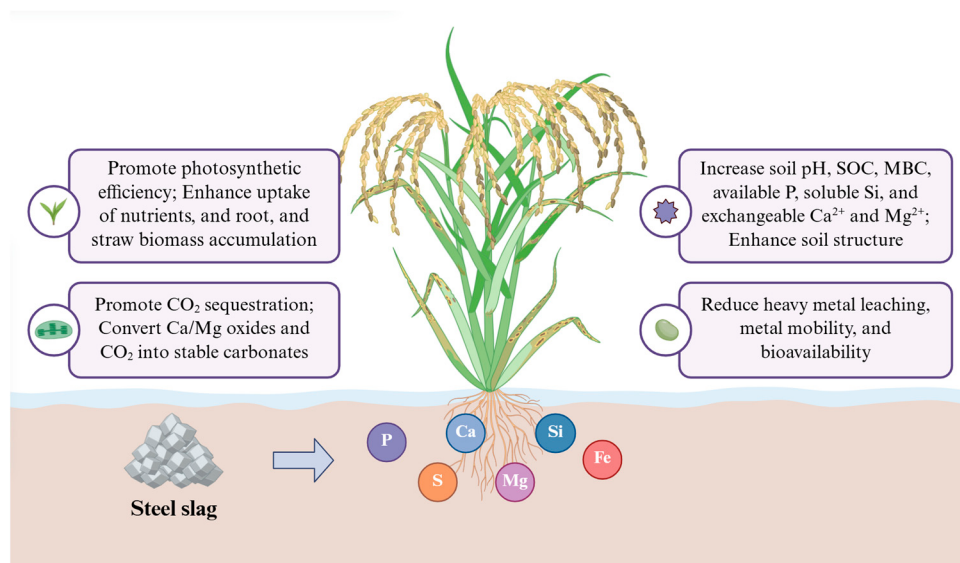


Figure 3. The impact of steel slag on soil properties and crop growth.

3.2.3. Potential Environmental Risks

The long-term use of SS in agricultural soils may pose significant environmental risks, such as the accumulation of heavy metals, the deterioration of soil quality, and potential

threats to food safety. Studies have shown that repeated applications of SS can result in the gradual accumulation of heavy metals such as Cr, Ni, Pb, Zn, and Cd in soils. Under certain environmental conditions, these metals may be taken up by crops and transferred through the food chain, thereby posing potential threats to human health [84]. In addition, the high viscosity and hydraulic setting properties of SS can negatively affect soil structures, leading to compaction, which hinders root development and reduces soil aeration [85].

3.3. Red Mud

3.3.1. Composition and Properties

Red mud (RM) is a highly alkaline residue of alumina refining through the Bayer process. In 2022, global RM production reached 172 million tons, with a cumulative new output exceeding 2.327 billion tons, posing a significant environmental challenge due to its large-scale stockpiling [86]. The wet storage of RM risks the leaching of alkaline solutions into groundwater, while dry storage, although more common, may lead to the airborne dispersion of fine particles and resultant air pollution [87]. RM is rich in metal oxides like SiO_2 , Al_2O_3 , TiO_2 , and Fe_2O_3 , and exhibits a porous structure with abundant surface hydroxyl groups. The strong alkalinity (pH 10–13) and distinctive surface properties of RM contribute to its capacity to stabilize heavy metals in contaminated soils. However, its extreme alkalinity and high treatment energy demand have limited its utilization rate in agricultural and environmental applications [88].

3.3.2. Effects on Soil Properties and Plant Growth

As a highly alkaline industrial by-product, RM possesses a large specific surface area, a strong adsorption capacity, and abundant oxygen-containing functional groups, making it frequently used for the remediation of heavy metal-contaminated soils. Lombi et al. reported that RM application reduced the concentrations of Zn, Ni, and Cu in both soil pore water and lettuce tissues while promoting microbial proliferation [89]. Friesl et al. found that RM significantly decreased exchangeable Cd, Zn, and Ni in sandy soil by 70%, 89%, and 74%, respectively, and reduced their accumulation in plants by up to 87% [90]. Li et al. showed that 0.4% (*w/w*) of RM application under high fertilization conditions reduced shoot Cd content and bioaccumulation by 30.0% and 28.5%, respectively, while enhancing the total nitrogen (+16%) and vitamin C content (+20.9%) in *Brassica campestris* L., indicating dual benefits in heavy metal mitigation and crop quality improvement [91]. Overall, red mud has good fixation effects in the treatment of heavy metal-contaminated soils and can also improve the soil nutrient environment as well as crop quality to a certain extent, which makes it a resource utilization material with both environmental and agricultural value.

3.3.3. Potential Environmental Risks

The concentrations of potentially toxic elements (PTEs) in RM vary significantly depending on its origin. Typically, red mud contains elevated levels of Cu, Pb, and Zn, while As and Cr are also commonly present. Even at low concentrations, the highly toxic elements, like As and Cr, can pose serious risks to both ecosystems and human health [92]. The radionuclide content in red mud is also a key environmental concern for its application in soils. Studies have shown that applying red mud at rates of 60 and 480 t·ha^{−1} increased the activity concentration of ²²⁸Th in sandy soils from 8 Bq·kg^{−1} (control) to 13 and 71 Bq·kg^{−1}, respectively, while the corresponding ²²⁸Th activity concentrations in lettuce samples were 1.9, 1.8, and 3.3 Bq·kg^{−1} [93]. Although these radionuclide levels are relatively low, further studies are needed to evaluate the long-term environmental impacts of red mud application from different sources.

3.4. Phosphogypsum

3.4.1. Composition and Properties

Phosphogypsum (PG) is an acidic by-product generated from the wet-process production of phosphoric acid. It typically appears as a gray, moist, and finely textured material resembling silt or silty sand. It is estimated that for every 1 ton of phosphoric acid produced, approximately 4.5–5.5 tons of PG are generated, indicating that the volume of PG often exceeds that of the primary product [94]. PG mainly consists of calcium sulfate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), which accounts for more than 90% of its total content. Owing to its high solubility ($\sim 2.5 \times 10^2 \text{ mg} \cdot \text{L}^{-1}$), PG can supply key plant nutrients such as P, Mg, Ca, Fe, Zn, Mn, and Si, which can infiltrate into deeper soil layers through leaching, thereby improving soil fertility and promoting root development [95]. Nevertheless, minor minerals and impurities introduced during raw material processing may result in the presence of trace heavy metals such as Cu, Zn, Pb, Cd, As, and Hg in PG. Under certain environmental conditions, these elements may reach concerning concentrations, posing potential ecological risks to soil systems [96].

3.4.2. Effects on Soil Properties and Plant Growth

As an acidic by-product rich in Ca, S, and P, PG is widely applied in agriculture for soil amelioration and saline-alkali land remediation [97]. Wu et al. reported that PG optimized soil salinity compositions by increasing Ca^{2+} and K^+ levels, reducing Na^+ , CO_3^{2-} , and HCO_3^- concentrations, and lowering soil pH via sustained SO_4^{2-} release, thereby promoting wheat growth [98]. Da Costa et al. found that PG, especially when co-applied with lime, improved the fertility and yield of maize and cowpea by enhancing reproductive organ development [99]. In saline-alkali soils, the abundant Ca^{2+} in PG effectively displaces Na^+ , reducing ESP, while its acidity helps neutralize soil alkalinity [68]. Al-Enazy et al. showed that PG combined with PGPR lowered the pH and electrical conductivity (ECe) of soils, increased the available P and K, and boosted maize dry weight by 82.1% to 127.4% [100]. Similarly, Smaoui-Jardak et al. found that applying 80% of PG reduced soil ECe by 25.5% [101]. In addition, PG can be combined with other functional materials to further enhance its soil amelioration performance. A saline-alkali soil remediating agent (SSRA) composed of PG, attapulgite (ATP), sodium polyacrylate (SP), and weathered coal (WC) improved the soil's capacity to retain water and nutrients by forming hydrogen bonds with the water molecules, urea, or ammonium chloride in the soil. In addition, it reduced soil salinity through ion exchange and immobilization, and alleviated alkalinity by adjusting the soil's pH, ultimately promoting the growth of maize crops [102].

3.4.3. Potential Environmental Risks

Certain PG contains various impurities, including radioactive elements (Ra-226, Rn-222, Pb-210, Po-210, and U-238) as well as heavy metals such as Cd, Pb, Cr, and As. Also, the presence of soluble fluoride (F^-) poses a risk of leaching into groundwater, which can ultimately enter the food chain and cause dental and skeletal fluorosis in humans. Consequently, the large-scale use of untreated PG raises considerable concerns regarding environmental and food safety risks [103]. For instance, Enamorado et al. (2014) conducted a comprehensive study on the uptake of 25 elements, including Be, B, Al, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Sr, Mo, Ag, Cd, Sb, Cs, Ba, Tl, Pb, Th, and U, in soils treated with PG during tomato cultivation. The findings revealed that increasing the PG application rate significantly elevated the soil's concentration of Cd, which was subsequently translocated into both the aerial tissues and fruits of tomato plants [104].

In summary, industrial wastes such as fly ash (FA), steel slag (SS), red mud (RM), and phosphogypsum (PG) exhibit promising potential as soil amendments, capable of

improving the physicochemical properties of soil, enhancing its nutrient availability, and increasing crop productivity. However, due to their complex composition and potential environmental risks, direct application to soil without appropriate stabilization or risk control may lead to serious environmental concerns, including heavy metal accumulation, radionuclide enrichment, the structural degradation of soils, and ecological toxicity. Similarly, certain types of biochar may also pose potential risks when applied directly without modification or co-treatment. The advantages and disadvantages of various waste materials are summarized in Table 1. These concerns highlight the necessity of rigorous pretreatment, comprehensive risk assessment, and long-term environmental monitoring prior to their widespread use in agricultural applications.

Table 1. Advantages and risks of applying single biochar or industrial waste.

Type of Wastes	Advantages	Risks	References
Sewage sludge biochar (SSB)	Enriches soil with N and P; Reduces availability of certain heavy metals; Provides functional groups for pollutant sorption	Introduces heavy metals (e.g., Zn, Cd, Cu), PAHs, antibiotics, or pathogens into soil	[60,61]
Animal manure biochar (AMB)	Supplies bioavailable nutrients; Enhances soil structure and fertility	Raises soil pH excessively; Reduces nutrient availability in fertile soils	[61,65]
Fly ash (FA)	Improves soil pH, fertility, porosity, and crop yield; Increases availability of P, K, Mg, Zn, and Mn	Leaches heavy metals (e.g., Zn, Cd, Pb) under carbonation or landfill conditions	[73,74,78]
Steel slag (SS)	Supplies nutrients (P, Fe, Ca, Mg, Si); Increases soil pH and organic carbon; Enhances CO ₂ sequestration and crop productivity	Accumulates toxic metals (e.g., Cr, Ni, Pb, Zn, Cd); Compact soil and reduce aeration	[82–84]
Red mud (RM)	Reduces heavy metal bioavailability (e.g., Cd, Zn, Ni); Improves microbial activity and crop quality	Releases radionuclides (e.g., ²²⁸ Th) and toxic metals (e.g., As, Cr) into soils and crops	[89,90,92,93]
Phosphogypsum (PG)	Remediates saline-alkali soils; Provides Ca, S, and P; Lowers pH and improves crop biomass	Leaches radioactive elements and fluoride into groundwater; Transfers toxic metals into edible plant tissues	[98,100,103,104]

4. Advantages of Biochar-Industrial Waste Composites for Soil Improvement

Biochar, as an agricultural soil amendment, exhibits excellent water retention, nutrient retention, and heavy metal adsorption capabilities, making it widely used in the remediation of acidified, infertile, and polluted soils. However, the nutrient release from biochar after application is limited, and it often needs to be combined with chemical fertilizers, which increases its application costs to some extent [105]. Although its preparation cost is lower than some traditional amendments, price and resource availability remain the limiting factors for its large-scale adoption. Industrial wastes such as fly ash, steel slag, red mud, and phosphogypsum, which are rich in nutrients like calcium, silicon, phosphorus, and sulfur as well as possess strong metal ion exchange/adsorption abilities, demonstrate significant potential for soil improvement. However, due to their complex composition, they often contain potentially harmful elements like arsenic, cadmium, and lead. If applied to agricultural lands without stabilization, they may lead to the accumulation of heavy metals in the soil, ultimately impacting crop safety and ecological health [106,107].

The co-application of biochar and industrial waste effectively addresses the limitations of both. On the one hand, biochar's strong adsorption properties can immobilize heavy metals released from industrial waste, reducing environmental risks. On the other hand, the inorganic nutrients abundant in industrial waste can enhance the nutrient content and improve the potential of biochar. This synergistic application helps to lower soil

improvement costs and promotes resource recycling, achieving a win-win outcome for both environmental and economic benefits.

4.1. Interaction Mechanisms Between Biochar and Industrial Wastes

4.1.1. Biochar and Fly Ash

Biochar has been shown to effectively inhibit the volatilization of potentially toxic elements (PTEs) in fly ash. Yousaf et al. demonstrated that biochar could effectively inhibit the volatilization of PTEs like As, Cd, Pb, Cr, and Zn in fly ash through the following mechanisms: (1) surface oxygen functional groups of biochar adsorb and fix PTEs via charge interaction; (2) precipitation reactions promote the stabilization of PTEs; (3) ion exchange further reduces the volatility of PTEs; and (4) biochar provides a stable carbon source, increasing the fixed carbon pool and promoting the precipitation of PTEs [108]. Fly ash, as a soil amendment, can also serve as a catalyst when used in combination with biochar, reducing the activation energy during the pyrolysis process, increasing gas production, and improving the water retention properties of biochar simultaneously [109].

4.1.2. Biochar and Steel Slag

The combination of biomass materials with steel slag has been shown to significantly improve its physical properties, thereby enhancing its potential for soil remediation. Wang et al. reported that incorporating biomass-derived materials, such as straw biochar, nutshell biochar, and humic acid, into SS led to the formation of finer surface deposits, multilayered porous textures, and distinct surface fissures. These structural changes result from the migration and accumulation of iron–calcium phases from SS onto BC, thereby enhancing its porosity and specific surface area. Additionally, the increase in carbon content on the modified steel slag surface introduces more organic functional groups, enhancing the material's bioactivity and metal chelation capacity, which helps improve soil structure and increases soil fertility [110]. Wang et al. found that after the co-pyrolysis of SS and BC, metals like Ca, Mg, and Fe from the SS could attach to the BC's surface, forming abundant oxygen-containing functional groups. This co-application directly influences the size and species composition of methanotrophic populations, reducing methane emissions by improving soil properties and promoting methane oxidation [13].

4.1.3. Biochar and Red Mud

Biochar produced via hydrothermal treatment possesses abundant oxygen-rich surface functionalities and a porous structure, which can enhance the adsorption capacity for RM through surface processes such as precipitation and ion exchange [111]. By co-pyrolyzing biomass with RM, the adsorption properties of RM can be utilized to immobilize heavy metals (HMs) in the biochar while simultaneously enhancing the stability of the BC. Li et al. investigated the synergistic mechanism of the co-pyrolysis of RM and biomass for preparing a biochar to immobilize heavy metals (HMs) and enhance biochar stability. Their study showed that co-pyrolysis treatment could significantly improve the oxidation resistance of biochars and increase the stable forms of Ni, Cr, and Cd in the RM. The metals in the RM catalyzed the pyrolysis of corn stalks, promoting the formation of condensed aromatic carbon structures. Heavy metals were immobilized by coordination adsorption to form carbon–metal or metal oxide complexes, thus stabilizing heavy metals and enhancing biochar stability, reducing phytotoxicity [112].

4.1.4. Biochar and Phosphogypsum

The surface of biochar typically exhibits electronegativity. When combined with phosphogypsum (PG), the PG + BC becomes positively charged under acidic conditions, enabling the adsorption of negatively charged heavy metal pollutants such as PO_3^{2-} ,

$\text{Cr}_2\text{O}_7^{2-}$, and HCrO_4^- [113]. The addition of PG also improves the conductivity, enhances the H/C ratio, and promotes cation exchange on the surface of the biochar. This introduces abundant O and Ca-containing functional groups to the biochar, further enhancing its ability to adsorb and immobilize heavy metals [114]. A study by Guo et al. found that biochar has abundant pores and an excellent electron transfer capacity. The combination of biochar and phosphogypsum (BC/PG) could aggregate PG and disperse it on the biochar surface, increasing the possibility of reactions between BC/PG and metal ions. The accelerated electron transfer from biochar promoted the binding of Pb^{2+} with P, S, and F elements released from PG, further promoting the transformation of Pb minerals into pyromorphite precipitation, thereby achieving Pb passivation [115].

4.2. Effects of Biochar-Industrial Waste Composites on Agricultural Soils

The effects of soil amendments on agricultural soils are typically manifested by promoting plant growth by enhancing soils' chemical and physical traits as well as its nutrient status, enhancing soil health by improving microbial species and abundance as well as enzyme activity and removing heavy metals and organic compounds through adsorption. Different biochar–industrial waste composite soil amendments have distinct physicochemical properties, leading to varying roles and effects in the soil environment.

4.2.1. Amendment of Acidic and Saline/Alkaline Soils

For acidic soils, alkaline soil amendments are recommended, as they contain more salt ions that can lower the hydrogen ion concentration in the soil and reduce the levels of exchangeable aluminum ions. For example, Lu et al. prepared a sludge biomass biochar and peanut straw biochar using an anaerobic pyrolysis method and studied the effects of SS and BC, both alone and in combination, on improving the acidity of red soil. The results exhibited that the addition of these three alkaline amendments could effectively neutralize soil acidity, increase the exchangeable base cations, and reduce the exchangeable aluminum in soil. Among them, the combination of SS and peanut straw was the most effective in improving soil acidity, increasing soil pH by 2.14, while the single application of sludge biomass biochar showed the least improvement [116]. Masto et al. conducted a field experiment on acidic red soil in Dhanbad, India, to investigate the impact of applying lignite fly ash (LFA), biochar (BC), and their combination on the soil's nutrients, biological properties, and maize yield. The results showed that the combination of LFA and BC significantly increased the nutrient content of phosphorus (+110%) and potassium (+64%) required for plant growth. It also enhanced soil enzyme activity, including dehydrogenase (+60.7%), alkaline phosphatase (+32.2%), fluorescein hydrolysis enzyme (+12.3%), and microbial biomass (+25.3%). Moreover, the application of LFA + BC increased the soil's pH, which in turn helped reduce the concentration of available heavy metals (Zn, Ni, Co, Cu, Cd, and Pb) in the soil through surface adsorption and precipitation. The application of LFA alone had no significant impact on maize yield, while the sole application of BC increased maize yield by 11.4%. However, when BC and LFA were applied together, the maize yield increased significantly by 28.1% [117].

For alkaline soils, acid soil amendments are commonly used to neutralize excess OH^- in the soil. Mao et al. studied the effects of BC, PG, and earthworm castings as soil amendments on the improvement of saline-alkali soils in Jilin. The results showed that the free phosphoric acid in PG and Ca^{2+} reacting with alkaline carbonates could effectively reduce the pH of saline-alkali soils. Although BC is alkaline and not very effective in lowering soil pH, its buffering effect allowed the soil's pH to decrease slightly in the later stages of the experiment. Earthworm castings, which were rich in microorganisms, improved the soil's cation exchange capacity and effectively enhanced its physicochemical

properties. The best soil amendment combination, based on comprehensive evaluation, was found to be 8% of PG, 6% of corn stalk biochar, and 10% of earthworm castings [118].

Furthermore, due to BC's alkaline nature, adjusting the ratio of BC to PG can produce soil amendments with varying pH levels, which can also be applied to acidic soils. Panda et al. studied the application of a banana stalk biochar–phosphogypsum composite (BPC), prepared by co-pyrolysis at 700 °C, to acidic red soil. The results showed that the soil pH ranged from 2.34 to 4.55 for the PG-treated group during the 1–41 days of incubation, while BC helped to reduce soil acidity. The combined BPC increased the soil pH to 7.69–8.56. The addition of PG also increased the plant-available sulfate content in the soil leachates, improving soil fertility. Additionally, due to the presence of Ca^{2+} and SO_4^{2-} in PG, its application helped to alleviate aluminum toxicity and, when combined with BC, could fix heavy metals in the soil and reduce their leaching concentration [119].

4.2.2. Remediation of Heavy Metal Contaminated Soils

With increasing industrial and agricultural activities, heavy metal contamination in soils has become widespread. Biochar–industrial waste composites have shown strong potentials for remediation. Cao et al. investigated the co-remediation of Cd and As in rice fields under different water regimes. Under continuous flooding, the combined application of steel slag and biochar (CF + SS + BC) significantly reduced the Cd and As levels in rice. This was attributed to the reducing conditions created by SS and BC, where SO_4^{2-} was converted to S^{2-} forming CdS, and CO_3^{2-} reacted with Cd^{2+} to form CdCO_3 . Additionally, BC adsorption and Ca co-precipitation suppressed As release under reduction [120]. Also, Wang et al. synthesized a biochar-modified steel slag composite (SS-BC) for the remediation of Pb- and Cd-contaminated soils. The optimal dosage (3 g/kg) achieved passivation efficiencies of 51.76% for Pb and 63.74% for Cd within 60 days. The SS-BC treatment greatly decreased the acid-extractable fraction of heavy metals and increased their residual form, lowering the ecological risk index of Cd from 606.13 to 69.74. In rapeseed cultivation, SS-BC enhanced plant height, the fresh and dry biomass, chlorophyll, and nitrogen content, while reducing heavy metal uptake and translocation. The mechanisms included heavy metal fixation, soil fertility improvement, and nutrient release, ultimately boosting crop growth and yield [121].

In addition, composite soil amendments can alter the distribution of heavy metal forms, reducing their activity and impact on soil and plants. Li et al. applied silkworm sand, RM, and their combination to Pb- and Cd-contaminated soils. The results showed that the silkworm sand increased the soil's organic matter content, while RM improved the pH of the soil. Both amendments promoted the conversion of Pb and Cd from more plant-available forms to less toxic residual forms, increasing the height and dry biomass of pak choi as well as reducing Pb and Cd absorption. The combined treatment of silkworm sand and RM was more effective in heavy metal passivation than the individual applications, with the best combination being 3% of silkworm sand and 1% of RM [122]. Weng et al. used different ratios of sugarcane bagasse biochar and RM to prepare composite soil amendments. The results showed that the amendments reduced the proportion of bioavailable Cd, Zn, and Cu in the soil while increasing their stable forms. This reduced the bioavailability of heavy metals and decreased the concentrations of Cd, Zn, and Cu in eucalyptus roots, enhancing the biomass and chlorophyll content of the trees [123]. Zou et al. conducted soil incubation experiments to investigate the effects of BC, RM, and RM-modified BC on arsenic (As) contaminated soil. Their results indicated that BC alone increased the NaHCO_3 -extractable As concentration by 23%, while RM increased it by 6%. In contrast, the RM-modified BC reduced the extractable As concentration by 27%, showing similar trends for HCl-extractable As. The RM-modified BC also increased the relative abundance

of Proteobacteria and its associated genera, such as Kaistobacter, Rhodanobacter, and Rhodoplanes, which play significant roles in the reduction in Fe(III) minerals and the release of As [12].

BC combined with industrial solid waste also acts as a stabilizer. For example, Moon et al. used calcined oyster shells (COSs) and steel slag (SS) to stabilize As-, Pb-, and Cu-contaminated soils. The COSs served as primary stabilizers, while SS was a secondary stabilizer. The results showed that SS alone (10 wt%) did not significantly stabilize the soil, but when combined with the COSs, the leaching concentrations of As, Pb, and Cu were significantly reduced. The best stabilization was achieved with 15 wt% of COSs and 10 wt% of SS. The stabilization of As was due to the high concentration of pH and Ca provided by the COSs, and Fe from the SS formed Ca-Fe(III)-arsenate complexes, which are less soluble at a high pH than simple iron arsenates. The fixation of Pb and Cu likely occurred through reactions with calcium silicate hydrates and calcium aluminate hydrates [124]. Ma et al. synthesized biochar composites (ABs) from alkali-fused fly ash (AFFA) and corn straw (CS) via co-pyrolysis and tested their ability to remediate Pb-contaminated soils. The results showed a significant reduction in the Pb content of the soil after applying ABs. The stabilization of Pb was mainly achieved through electrostatic adsorption, precipitation, cation- π interactions, cation exchange, and complexation. Additionally, the increases in the soil's pH and CEC were correlated with the reduction in Pb, further confirming that ABs help improve soil properties and facilitate Pb stabilization, as illustrated in Figure 4 [125]. In summary, biochar composite materials synthesized from industrial and biomass waste provide a promising solution for the management of heavy metal pollution in agricultural soils.

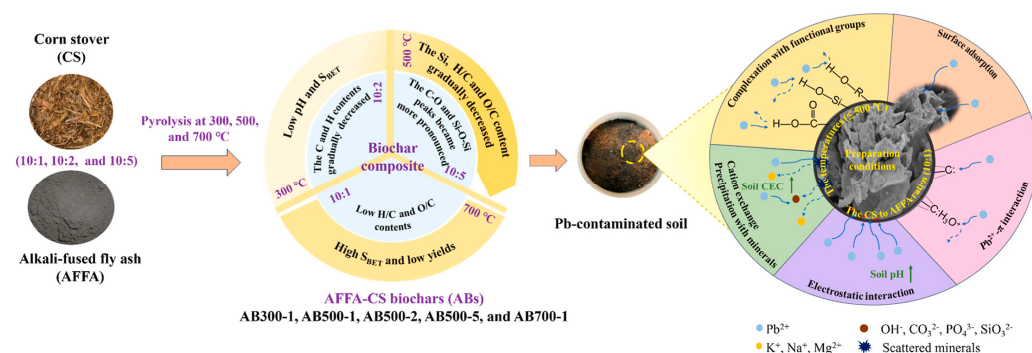


Figure 4. Stabilization of Pb-contaminated soil using biochar and fly ash composite amendments. Reproduced from [125] with permission.

4.2.3. Improvement of Low Fertility Soils

The addition of biochar-industrial waste composites not only improves soil pH and passivates heavy metal pollutants but also increases nutrient elements in the soil, thereby enhancing soil fertility. Munda et al. examined how rice husk (BC) and FA influenced rice performance and soil quality in lowland conditions. Compared with the use of sole chemical fertilizers, the integrated application of BC, FA, and fertilizers significantly improved plant development and productivity. Notably, replacing half of the recommended nitrogen input with BC + FA resulted in a 16.4% yield increase. Post-harvest soil assessments revealed that both amendments functioned as sources and reservoirs of nutrients [126]. Vimal et al. synthesized PL biochar using banana pseudostem biomass (BP) and phosphogypsum (PG) to simultaneously enrich K, S, and Ca nutrients. The results showed that K from BP, as well as S and Ca from PG, could be retained and enriched through the formation of K₂SO₄ and CaSO₄. Additionally, the co-pyrolysis process formed K₃PO₄, and this composite material

also contained a higher proportion of soluble P, whose slow release could improve nutrient utilization efficiency and has great potential in promoting seed germination [127].

4.2.4. Impact on Soil Carbon Sequestration

Recently, biochar has been recognized as a strategy for carbon sequestration and mitigating climate change. The addition of biochar combined with industrial waste, such as steel slag, to agricultural soils has been employed to enhance soil organic carbon (SOC) storage while sustaining crop growth. Numerous studies, including laboratory and field trials, have highlighted the significant impact of biochar on active SOC, particularly related to microbial activity in paddy soils. For instance, Wang et al. used real-time quantitative PCR and high-throughput sequencing techniques to assess the effects of slag + biochar (SS + B) amendments on CH₄ emissions, abundance, and methanotrophic community structure, as well as their relationships with soil properties [13]. Also, Wang et al. investigated the effects of SS + B amendments on total soil CO₂ emissions, SOC content, and active microbial communities in subtropical rice paddies. The results indicated that, despite external carbon inputs from the amendments, CO₂ emissions were reduced compared to the control (41.9–59.6% reduction in the early season), mainly due to an increased soil pH and the enhanced abundance of *Agrobacterium*, *Streptomyces*, and *Gluconacetobacter*, which are crucial for promoting carbon assimilation, improving carbon stability, and achieving soil carbon sequestration while reducing CO₂ emissions in paddies [128].

Lin et al. focused on early and late rice paddies and explored the impacts of steel slag (SS), biochar (B), and SS + B treatments on total SOC, active SOC fractions, and soil microbial communities. The results showed that during both the early and late seasons, SS, B, and SS + B treatments increased soil salinity by 26–80%, 1.3–37%, and 42–79%, respectively, while soil pH was increased by 0.8–5.7%, 2.1–2.4%, and 4.0–6.3%, compared to the control. The SOC concentrations in all treatments were higher than in the control, ranging from 4.3 to 5%, 0.5 to 17%, and 4.3 to 7%, respectively. In the late rice season, the SS + B treatment resulted in a significant decrease in active carbon pools and the carbon pool management index, by 26.3% and 21.3%, respectively, suggesting that the amendments contributed to soil carbon storage [129]. This may be due to the increased concentration of oxidized iron in the soil, which forms more chemical bonds to enhance SOC stability, along with the oxygen-containing functional groups from BC (e.g., -COOH) that react strongly with soil minerals [130]. Additionally, the increased soil aggregation helps physically protect the SOC from microbial degradation. The combined addition of slag and BC may reduce the abundance of potential SOC-degrading microbes and increase microbial carbon use efficiency, thereby stabilizing the active SOC and promoting long-term carbon sequestration [129]. However, some studies suggest that the carbon sequestration effect of the SS + B application is less evident in late rice paddies. For example, Wang et al. found that the SS + B treatment increased the SOC by 28.7% and 42.2% in the early and late rice seasons, respectively, and raised the carbon pool index (CPI) by 22.4% and 40.1%. During the early season, the carbon pool activity index (CPAI) and carbon pool management index (CPMI) decreased significantly, by over 50% and 36.7–45.4%, respectively. However, in the late season, no significant differences in the CPAI and CPMI were observed across the treatments [131], indicating a limited carbon stabilization effect in the late-season rice fields.

In summary, the combined application of biochar and industrial waste offers greater advantages than their individual use. The effects of such applications across different soil types are summarized in Table 2.

Table 2. Comparison of Biochar–Industrial Waste Composites for Soil Amendment.

Composite Type	Preparation Method	Soil Type	Main Effects	Potential Risks	References
Peanut straw + Steel slag	Pyrolysis	Acidic red soil	Neutralizes soil acidity; Increases exchangeable K, Ca, Mg and salt-based ions; Reduces exchangeable Al ³⁺	-	[116]
Lantana camara + Lignite fly ash	Mix	Acidic red soil with sandy loam texture	Improves plant-available P and K levels; Enhances soil enzyme activity; Promotes soil pH and decreases bioavailable heavy metals (Zn, Ni, Co, Cu, Mn, Cd, Pb)	-	[117]
Corn stalk + Earthworm dung + Phosphogypsum	Mix	Saline-alkali Soil	Lowers soil pH and exchangeable Na ⁺ ; Increases soil CEC	-	[118]
Banana peduncle + Phosphogypsum	Co-pyrolysis at 700 °C	Acidic red soil	Increases soil pH and plant bioavailability of nutrients; Alleviates Al toxicity; Immobilizes soil heavy metals	-	[119]
Corn stalk + Steel slag	Pyrolysis at 500 °C	Topsoil of farmland with Pd and Cd	Passivates Pb and Cd in soil; Enhances plant height, biomass, chlorophyll, and nitrogen content; Reduces heavy metal accumulation in crops	Heavy metal leaching risks	[121]
Biochar + Steel slag	Mix	Pb- and As-contaminated paddy soil	Increases soil pH; Decreases Eh; Reduces Cd concentration in soil solution; Inhibits rice uptake of Cd and As	Increases As concentration in soil solution	[120]
Silkworm sand + Red mud	Mix	Pb-, and Cd-contaminated soil	Improve soil organic matter and pH; Promote transformation of Pb and Cd from exchangeable to residual forms; Enhance height and dry biomass of pak choi	-	[122]
Sugarcane bagasse + Red mud	Mix	Cd-, Zn-, and Cu-contaminated soil	Reduces bioavailability of Cd, Zn, and Cu in soil; Increases biomass	-	[123]
Oyster shells + Steel slag	Calcine	As-, Pb-, and Cu-contaminated soil	Reduces leachability of As, Pb, and Cu; Forms Ca-As and Fe-As precipitates for As immobilization; Promotes pozzolanic reactions for Pb and Cu stabilization	-	[124]
Corn stover + Alkali-fused fly ash	Co-pyrolysis	Pb-contaminated soil	Reduces soil Pb concentration; Increases soil pH and CEC	-	[125]
Rice husk + Fly ash	Mix	Low-fertility soil	Improves soil pH, OC, CEC, EC and available N, P, K; Increases lowland rice yield	Fe, Mn, Zn, Cu, and Pb release risks	[126]
poultry litter + Banana peduncle + Phosphogypsum	Co-Pyrolysis	Low-fertility acidic red soil	Improves soil P, S, K, and Mg; Reduces the release rate of P; Increases nutrient utilization efficiency	-	[127]
Biochar + Steel slag	Mix	Agronomy paddy field	Increases soil pH, salinity, and SOC contents; Decreases active organic C and cumulative CO ₂ emissions; Increases abundance of microbial genera related to carbon assimilation	-	[128]
Biochar + Steel slag	Mix	Agronomy paddy field	Increases soil pH and salinity; Decreases active SOC pools; Enhances soil C sequestration	-	[131]

4.3. Role of Biochar-Industrial Waste Composites on Crop Growth and Yield

When applied individually, both biochar and industrial waste exhibit certain benefits but also face limitations. Their combined application can achieve enhanced effects through synergistic interactions, thereby fostering a more favorable soil environment for crop growth and yield enhancement. For example, Zhao et al. synthesized a red mud-based biochar composite (RMBC) using red mud (bauxite residue) and maize straw and found that the RMBC effectively immobilized heavy metals in the soil while promoting red onion growth. The order of efficacy was phosphorus-modified RMBC (PRMBC) > RMBC > BC > RM. PRMBC exhibited a superior Pb immobilization capacity due to the formation of insoluble Pb-containing compounds in the soil, thereby stabilizing the soil Pb content and minimizing Pb accumulation in the plant tissues [132]. Similarly, Yu et al. conducted a one-year field experiment on early and late rice in Xiangtan, China, to evaluate the effect of ash/biochar composite (A/B) on Cd-contaminated paddy soil. The results showed that A/B treatment significantly increased the soil pH and raised the available Si content by up to 22.9 times. The available Si was negatively correlated with the extractable Cd(II) in the soil and the Cd concentration in the rice plants, suggesting that Si may reduce Cd bioavailability via co-precipitation with metal ions. The enhanced Si availability also promoted rice growth and plant height, highlighting the potential of such composites to improve both crop productivity and food safety in contaminated soils [133].

By optimizing the composition of biochar-based amendments, soil fertility can be effectively regulated to support crop development. Yang et al. formulated several composite soil conditioners using quicklime, fly ash, steel slag, and biochar in varying proportions, and evaluated their effects on acidic vegetable field soils and the growth of romaine lettuce. The results demonstrated that these amendments significantly enhanced the soil organic matter, total nitrogen, available phosphorus, exchangeable potassium, and exchangeable magnesium. Correspondingly, the uptake of N, P, and K by the romaine lettuce increased by 7.94% to 64.79%, accompanied by yield improvements of 8.03% to 16.69%. Notably, the increase in nutrient uptake was positively correlated with crop yield, indicating that optimized nutrient availability played a critical role in improving productivity. The best performance was achieved with an amendment formulation containing $5.0 \text{ g} \cdot \text{kg}^{-1}$ of lime, $2.5 \text{ g} \cdot \text{kg}^{-1}$ of fly ash, $5.0 \text{ g} \cdot \text{kg}^{-1}$ of steel slag, and $50 \text{ g} \cdot \text{kg}^{-1}$ of biochar [134]. The effects of biochar-industrial waste composite soil amendments on promoting crop growth and yield are shown in Figure 5.

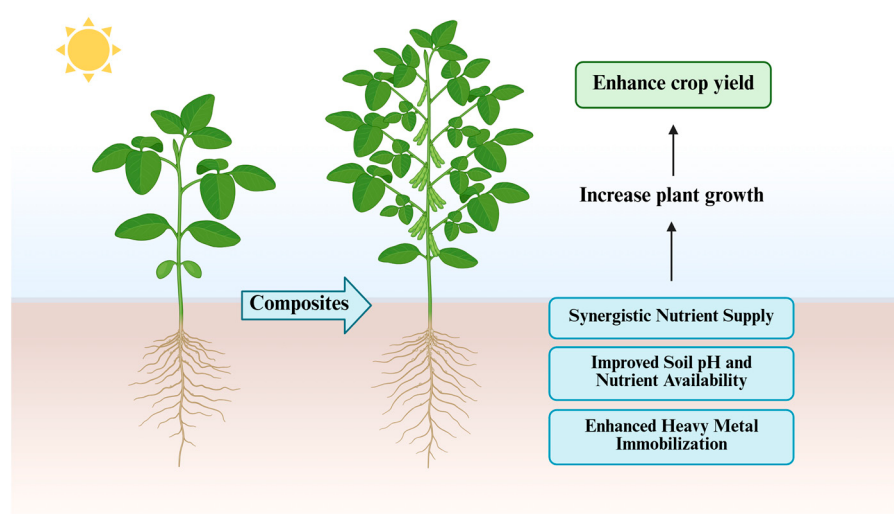


Figure 5. Effect of the composite amendments on plant growth and yield.

While biochar is widely used as a soil amendment, municipal compost, as another form of organic waste, is also considered an effective option for improving degraded soils, owing to its eco-friendliness, efficiency, and economic viability [135]. In recent years, more studies have highlighted that the combination of biochar and compost can effectively address issues such as water scarcity, soil compaction, nutrient deficiency, and contamination, thereby promoting crop growth. For instance, Kammann et al. reported a 305% increase in biomass yield in infertile soils after applying 2% (*w/w*) of co-composted biochar [136]. Schulz et al. found that adding 100 t/ha of biochar–compost mixture significantly enhanced oat growth in sandy and loamy soils [137]. Agegnehu et al. demonstrated that the biochar + compost treatment resulted in a significantly higher corn biomass compared to the sole application of biochar or chemical fertilizers, and the combined use was considered crucial for improving nutrient availability and plant uptake [138]. These findings showcase the potential of biochar and compost co-application in improving soil quality and promoting plant growth, contributing to the sustainable management of agricultural soils.

5. Challenges and Prospects of Co-Application in Agricultural Soils

5.1. *Challenges of Biochar and Industrial Waste Co-Application*

The co-application of biochar and industrial waste has shown great promise in improving soil fertility and remediating contaminated soils. However, its large-scale adoption still faces several key challenges, including environmental risks, technical limitations, and social promotion barriers.

5.1.1. Environmental Risks

The properties of biochar vary significantly depending on its feedstock and pyrolysis conditions. Biochar produced from sewage sludge or livestock manure may contain heavy metals (e.g., Pb, Cd, Zn, Cu) and polycyclic aromatic hydrocarbons (PAHs), which pose potential environmental risks due to leaching and long-term release through aging and microbial degradation [139,140]. Moreover, industrial wastes such as red mud, fly ash, and smelting slag may contain hazardous elements like As, Cr, U, and Ra [75,80,92,141]. Without appropriate treatment, their direct application to soil can lead to contamination and crop uptake risks.

5.1.2. Technical and Application Constraints

The formulation, dosage, and treatment methods of composite amendments require site-specific optimization. Currently, there is a lack of standardized technical protocols. The complex interactions between biochar–waste composites and different soil types, climates, and crops result in uncertain amendment outcomes [142,143]. Some industrial by-products require costly pretreatment (e.g., acid washing, stabilization), which limits their scalability in agriculture.

5.1.3. Adoption and Policy Barriers

In many developing countries, the use of biochar–industrial waste composites remains limited due to low farmer awareness, insufficient technical support, and weak policy incentives [144]. The lack of collaboration between government, academia, and farmers further hampers adoption. Additionally, challenges such as a limited transportation radius, high treatment costs, and weak market mechanisms restrict the practical application of such amendments.

To overcome these barriers, it is essential to establish environmental safety standards, develop standardized composite formulations, and build integrated frameworks involving

government, research institutions, and end-users to ensure the safe and sustainable use of biochar–industrial waste composites in agriculture.

5.2. Future Perspectives

Despite the promising performance of biochar–industrial waste composites (e.g., steel slag, fly ash, red mud, phosphogypsum) in improving and remediating agricultural soils, several scientific and practical issues still need to be addressed. Future research should focus on the following directions:

It is crucial to investigate potentially toxic components, including heavy metals and radioactive elements, within BC–industrial waste composites. Production conditions should be continuously optimized to reduce the risk of environmental contamination and ensure their safety for agricultural use and human health.

Current research mainly addresses surface-level improvements in soil properties, with limited understanding of the underlying interactions between the composites, soil, and plants. Future studies should emphasize the mechanisms of nutrient availability enhancement, heavy metal immobilization, and soil structure regulation. In addition, the optimal ratio and dosage of biochar and industrial wastes should be determined to support field-level applications.

Most existing studies are short-term or conducted on a limited field scale, lacking data on long-term environmental behaviors and agronomic impacts. Long-duration and regionally replicated field trials should be carried out to evaluate the persistence, ecological safety, and impact of such soil amendments on crop yield, soil health, and environmental sustainability.

The application of BC–industrial waste composites can be enhanced by integrating precision agriculture technologies such as remote sensing (RS) and geographic information systems (GIS) to achieve site-specific soil amendment. Moreover, incorporating regionally abundant waste materials (e.g., desulfurization gypsum, metallurgical slag, municipal sludge) into composite formulations could further improve cost-effectiveness and promote circular utilization of industrial by-products.

In summary, BC–industrial waste composites exhibit a synergistic green potential in improving soil quality and reducing environmental pollution. However, continued innovation and multidisciplinary research are essential to unlock their full potential and support sustainable agricultural development.

6. Conclusions

This review comprehensively summarizes the recent progress in the application of biochar–industrial waste composites (e.g., fly ash, steel slag, red mud, and phosphogypsum) for soil remediation and improvement. Evidence shows that these composites exhibit great potential in ameliorating acidic and saline soils, enhancing soil fertility, stabilizing heavy metals, promoting carbon sequestration, and improving crop productivity. Their effectiveness is attributed to the complementary physicochemical properties of biochar and industrial waste, making them environmentally and economically viable. However, challenges remain, including potential contamination risks, unclear mechanisms, and variable field applicability. Future research should focus on mechanistic understanding, formulation optimization, and long-term field validation, while leveraging digital agriculture tools to promote the large-scale, efficient, and sustainable application of these composite amendments in agricultural systems.

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Abbreviations

The following abbreviations are used in this manuscript:

BC	Biochar
FL	Fly ash
SS	Steel slag
RM	Red mud
PG	Phosphogypsum

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