C Journal of Carbon Research

MDPI

Review

Biochar in Agriculture: A Review on Sources, Production, and Composites Related to Soil Fertility, Crop Productivity, and Environmental Sustainability

Md. Muzammal Hoque [1,2,*], Biplob Kumar Saha [3], Antonio Scopa [1] and Marios Drosos [1]

[1] Department of Agricultural, Forestry, Food and Environmental Sciences (DAFE), University of Basilicata, Viale Dell'Ateneo Lucano 10, 85100 Potenza, Italy; antonio.scopa@unibas.it (A.S.); marios.drosos@unibas.it (M.D.)
[2] Bangladesh Institute of Nuclear Agriculture (BINA), Mymensingh 2202, Bangladesh
[3] Department of Agricultural Chemistry, Bangladesh Agricultural University, Mymensingh 2202, Bangladesh; bksaha@bau.edu.bd
* Correspondence: md.muzammal.hoque@unibas.it; Tel.: +39-351-2800433

Abstract

Due to soil nutrient depletion and rising food demand from an increasing global population, it is essential to find sustainable ways to boost crop yields, improve soil health, and address the environmental issues induced by agriculture. The most appropriate approach is to consider sustainable amendments, such as biochar and its derivatives, which are vital constituents of soil health due to their affordability, low reactivity, large surface area, and reduced carbon footprint. In this context, biochar and its derivatives in farming systems focus on improving soil structure, nutrient holding capacity, microbial activities, and the perpetuation of soil fertility. Despite its benefits, biochar, if it is used in high concentration, can sometimes become highly toxic, causing soil erosion due to reducing surface area, increasing pH levels, and altering soil properties. This review highlights the production methods and sources of feedstocks, emphasizing their important contribution to the soil's physicochemical and biological properties. Furthermore, it critically evaluates the environmental applications and their impacts, providing data built upon the literature on contaminant removal from soil, economic factors, heavy metal immobilization, carbon sequestration, and climate resilience. This review emphasizes the main challenges and future prospects for biochar use in comparison to modified biochar (MB) to propose the best practices for sustainable farming systems.

Keywords: biochar; carbon sequestration; soil health; sustainable farming; climate resilience

check for updates

Academic Editors: Sergey Mikhalovsky, Joaquín Silvestre-Albero, Rosa Busquets and Geoffrey D. Fowler

Received: 31 May 2025
Revised: 4 July 2025
Accepted: 8 July 2025
Published: 11 July 2025

Citation: Hoque, M.M.; Saha, B.K.; Scopa, A.; Drosos, M. Biochar in Agriculture: A Review on Sources, Production, and Composites Related to Soil Fertility, Crop Productivity, and Environmental Sustainability. *C* **2025**, *11*, 50. https://doi.org/10.3390/c11030050

1. Introduction

The main target of modern agriculture is to maintain a balance between environmental sustainability and productivity to feed the increasing population with nutritious food [1]. But high-yielding crops that use better varieties, fertilizers, irrigation, and pest control are necessary, as climate change threatens soil health and production. Maintaining soil fertility genuinely calls for a combination of synthetic fertilizers and organic amendments [2,3]. In recent years, biochar has really captured researchers' attention as a soil amendment, mainly because it offers a range of significant benefits [4].

Biochar is carbon-rich and made from biomass thermal treatment. It is beneficial to soil health by improving soil fertility, immobilizing pollutants, and enhancing the water-holding capacity [5]. Biochar can store carbon in soil for decades or even thousands of years, making it a highly effective long-term carbon sequestration solution. It is economical, accessible, and profitable, as well as environmentally friendly. The application of biochar is further justified by its absorption capability of complex heavy metals, due to the hydroxyl, carboxyl, and alcohol groups in its surface structure [6]. Some biochar is even able to absorb heavy metals as effectively or more effectively than commercially available activated charcoal, with a high adsorption capacity [7]. However, biochar has some disadvantages, such as its limitations and stability in soil. Wang et al. reported that non-volatile components can remain in soils for an average of 556 years, while labile components only last around 108 days [8]. Another limitation is the chemical recalcitrance imposed by aromatic structures. The biochar–soil interaction over a range of carbon levels remains poorly understood due to the diversity of soil types, variability in biochar species, and variability in geo-ecological experimental conditions. Chagas et al. conducted a meta-analysis, showing that biochar improves various soil characteristics, such as soil microbial carbon (200%), organic carbon (84%), and total carbon (64%) [9].

Advanced materials can be obtained by integrating biochar with other substances, which can enhance the surface area, porosity, and reactivity of biochar, making it useful for agricultural and environmental purposes [10,11]. To improve soil quality and facilitate carbon sequestration, as well as to support sustainable agriculture and climate change adaptation, scientists support the application of biochar together with other materials with synergetic properties [12,13]. Integrating them enhances heavy metal adsorption, the slow-release of nutrients, and the uptake of gases, such as CO_2 and CH_4, which help crops flourish without the risk of soil degradation. They provide essential nutrients to the soil, reduce the requirement for chemical fertilizer, and are less harmful to the environment, being consistent with green farming [13,14]. Biochar materials used in agriculture can improve soil properties and mitigate climate change; thus, they may contribute meaningfully to the advancement of sustainable and resilient agricultural system management worldwide [15,16].

This review highlights the role of biochar and its derivatives, which are biocompatible, long-lasting soil amendments, and their effects on soil structure, nutrient retention capacity, and potential for long-term fertility. Additionally, the review outlines the economic and associated benefits, as well as the environmental risks, of the various biochar derivatives. Furthermore, this review details the key barriers and future potential for adopting these materials as a soil improvement practice in sustainable climate-smart agriculture. To our knowledge, there has been no review that discusses both biochar and modified biochar, as well as their benefits and risks in sustainable agriculture, providing a perspective that is typically lacking in existing studies in the literature.

2. Historical Background of Biochar and Its Derived Composites

In 500 AD, people in the Amazon region created “Terra Preta”, a special type of soil amendment in which they mixed burned wood with fish bones and other food residues to increase the soil carbon holding capacity and improve soil fertility [17]. In the 17th and 18th centuries, some Europeans wrote about using charcoal in farming systems [18]. However, in the early 1900s, new plants took over, and the idea of biochar faded. In the 1980s and 1990s, interest in biochar resurfaced, as people hoped it could help retain carbon in soil. In the early 2000s, biochar studies grew, linked to its potential for carbon sequestration, soil structure improvement, and farming benefits to mitigate climate change [19]. From 2010 to the present, biochar has gained popularity as a natural-based option for farms and green agriculture practices [20,21].

Some research has demonstrated that combining biochar with other materials increases its value. Due to their enhanced properties, these materials can alter soil fertility, increase crop productivity, reduce greenhouse gas (GHG) emissions, and improve soil characteristics. They also have a tremendous positive impact on soil pH, nutrient cycling, water-holding capacity, and carbon sequestration [10,22]. When biochar-enhanced composites are used in the soil, many advantages have been observed, including the recovery of land contaminated with heavy metals, maintaining land productivity by increasing soil carbon, and improving on-farm efficiency and climate change mitigation, among other actions. They are considered improvements in soil management practices, as well as in soil restoration and the prevention of erosion, degradation, and desertification. Consequently, it can be expected that biochar will improve the immobilization process by working in synergy with other materials as a combined system, increasing the chances of achieving our target for soil restoration [13,23]. Modified biochar, such as engineered, designed, or smart biochar, is highly capable of absorbing contaminants from soil and water and facilitating carbon sequestration, while also maintaining soil health. Designed biochar is made from selecting feedstocks to obtain particular physical and chemical properties for targeted utilization, like biochar pellets, made from pyrolyzed nutshell under 500 °C, which are able to sequester carbon, especially from sandy soil. Engineered biochar is the combination of designed biochar with various chemical compounds and metals (Al, Mg, Ca, Fe, etc.). Adding these metals, biochar's characteristics will be enhanced, altering its properties, such as pH. For example, modifying biochar with oxygen plasma yields materials known as smart biochar, which are utilized in the life sciences, healthcare, and engineering [24–28].

3. Sources and Production Techniques of Biochar

3.1. Biochar Sources

Biochar can be produced through the pyrolysis of various organic materials. One of the primary sources of materials is agricultural residues, which can range from rice husks to wheat, corn, and cotton stalks. These are burned at low heat in household kitchens in an oxygen-limited environment to obtain biochar. Biochar source choice is vital to tailor its properties, as each feedstock has a different composition. Biochar from agricultural residues comprises carbon, plant fibers, and plant-specific components, such as cellulose (36–42%), hemicellulose (11–14%), and lignin (18–27%). It enhances soil health, absorbs carbon, lowers acidity levels, and increases nutrient retention capacity, yield performance (8–15.8%), nutrient usage efficiency (13.97%), nitrogen use efficiency (14.28%), and water utilization (14.28%) [29–31]. Forest residues, such as hardwood, sawdust, and bamboo, are used to produce biochar that contains a significant amount of carbon and has a large surface area. This enhances soil by increasing its water and air retention, reducing bulk, and helping roots breathe and access water. Wood biochar improves soil pH, contributes to an increase in organic carbon, holds nutrients, and promotes the growth of microorganisms. Bamboo biochar has remarkable potential to hold even more water, store carbon, and increase soil health for the long term [15,32,33].

Animal manure, including chicken litter, cow dung, and pig manure, is converted into biochar, which contains essential nutrients, such as phosphorus, potassium, and nitrogen. This biochar improves soil health, and cation exchange capacity (CEC), encourages microbes, and reduces dependency on synthetic fertilizers. Animal waste biochar positively affects soil health, increases the water-holding capacity, supports nutrient availability to plants, leads to higher crop yields, and has positive environmental outputs [34,35]. Urban waste materials, including food scraps and garden residues, can be converted into biochar via the application of heat, thus improving sustainable soil health. Food-waste biochar substantially enhances the fertility of soil, encourages the growth of microbes, and increases the water retention capacity [36]. Paper sludges, biosolids, and bio-oil residues from industry support the rehabilitation of contaminated soils by immobilizing heavy metals, increasing pH levels, and improving soil structure [37,38]. Agroforestry waste, including nut shells, palm materials, and coconut shells, enhances soil health and the sustainability of ecosystems by acting as carbon sequestration agents and providing permeable carbon matrices to enhance localized aeration [22].

3.2. Production Techniques

There are many different types of production techniques for biochar, such as hydrothermal carbonization (800–1200 °C) (HTC), gasification (600–1200 °C), drying (100–150 °C), torrefaction (200–300 °C), and pyrolysis (300–700 °C) [39]. Each of these strategies has advantages and disadvantages, so it is critical to understand which one works best for a given case. The pyrolysis process utilizes plant materials that are heated in the absence of air to produce char, gas, and liquid. The optimal temperature range is between 300 °C and 700 °C, with the best biochar formed between 400 °C and 600 °C. This biochar has high carbon content, a large surface area, and chelating centers. Pyrolysis is ideal for crops, holding carbon, and aiding in climate change mitigation [17,40,41]. Hydrothermal carbonization is the process in which wet materials are heated under high pressure to convert plant material into a carbon-rich biochar. This process operates between 180 °C and 250 °C, from 0.5 to 8 h, and is used to hold water and leach nutrients for plants [42]. Gasification is another method that burns plant material at high temperatures to produce char, gas, and tar. It uses little air and produces less char than pyrolysis, but saves energy. It is useful for generating power and avoids the spread of contaminants [43,44].

Flash carbonization is a faster method that heats plant bits quickly to make char. It operates more quickly than pyrolysis and necessitates a rapid heat buildup. For 20 min at temperatures ranging from 500 °C to 1000 °C, char with a large surface area and tiny holes is produced, which is excellent for trapping, facilitating reactions, and aiding the earth [45,46]. Cotton stalk (525 °C, 60 min, fixed bed reactor), rice straw (550 °C, 120 min, slow pyrolysis), wheat straw (425 °C, 60 min, vertical kiln), maize cob/husk (400 °C, 30 min, fixed bed reactor), corn straw (450 °C, 250 min, ceramic pots), sugarcane bagasse/leaves (575 °C, 60 min, electrical muffle furnace), and other biomass feedstocks can be thermochemically converted to biochar with better properties [39]. Magnetic biochar is produced at 450–1000 °C by soaking feedstock in Fe_2O_3, $FeSO_4{\cdot}7H_2O$, or $FeCl_3{\cdot}6H_2O$ before pyrolysis. This biochar serves as an effective adsorbent for contaminants and increases nutrient adsorption [47]. Sources and applications of biochar according to their specific contributions in various sectors, as well as the production techniques and pyrolysis temperatures, are summarized in Figure 1.

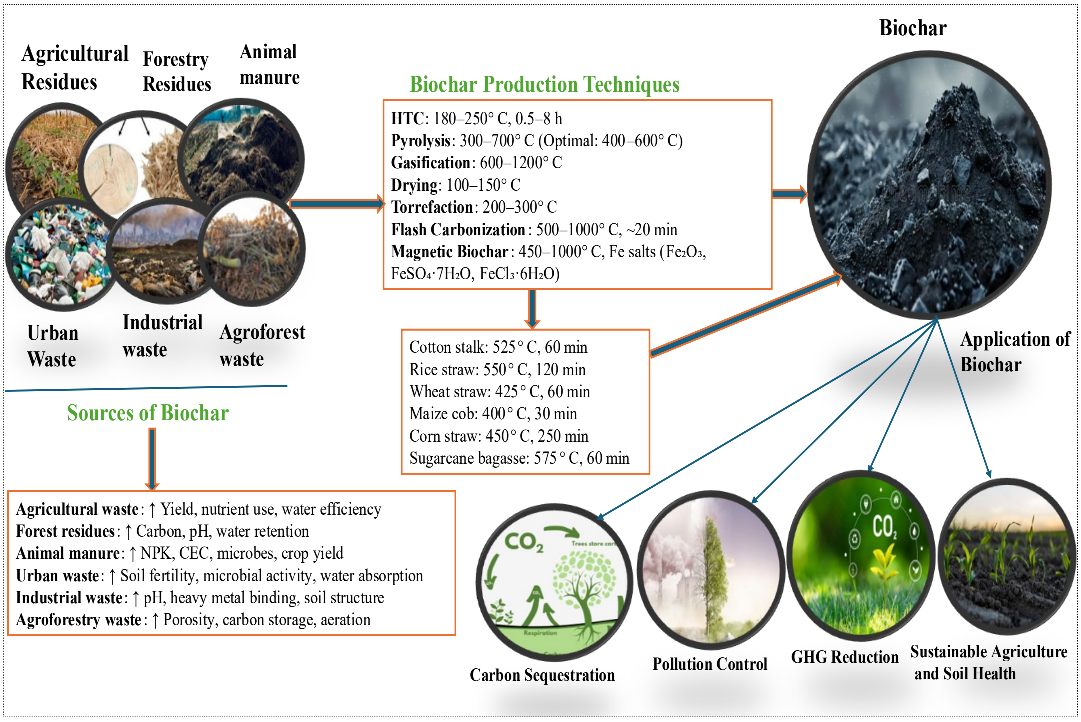

Figure 1. Biochar production techniques, sources, and applications.

4. Application of Biochar and Its Modified Materials in Agriculture

4.1. Soil Amendments and Fertility Enhancement

The evidence from several studies suggests that biochar improves soil structure, enhances soil fertility, and is beneficial for plant growth, making it a significant contributor to an energy-efficient future. Depending on the type of soil and the rate of addition, biochar can increase porosity by 14–64% and decrease bulk density by 3–31%. The application of 20% biochar to sandy soil will nearly double its water-retention ability and will also significantly decrease water erosion and soil losses. These changes improve nutrient availability, boost beneficial microbes, and promote soil management [48–50]. In an analysis conducted on 999 data pairs, when biochar is mixed with low-grade nutrient-rich organic wastes at low temperatures, it shows a positive effect of biochar on microbial biomass enhancement. Increased soil quality caused by an increased cycling of nutrients is also something that researchers have found in biochar [40]. It is capable of enhancing the microbial biomass, which means that it can promote the nitrogen cycle, resulting in 40.8% and 12.7% nitrification and N_2O reductions, respectively. There is also a possibility for biochar to interact with fertilizers, amendments, lime, agrochemicals, and microbes, where it reduces N leaching but may cause N immobilization due to high C/N, supplies or adsorbs P, and provides slow-release K [51]. With the introduction of biochar, it was discovered that the relative percentage of Actinobacteria decreased and the percentage of Basidiomycota increased, thus benefiting trees [52]. Recent research showed that wheat biochar plus pig manure (WBSC) and maize biochar plus pig manure (MBSC) improved oil quality by raising the oleic acid by 45% and lowering the linoleic acid by 79%, in comparison to raw biochar, which showed no effect. Biochar improved soil enzyme activity by 3.7–5.5%, but a biochar–compost mixture raised it by 6.4–10.1%. More specifically, the hydrolase-to-non-hydrolase ratio increased by 11.4–15.9% (biochar) and 20.5–25.0% (biochar-compost); C/N cycling rose by 20.9–33.8% and 17.4–39.0%; and P cycling improved by 14.7–23.5% and 23.5–32.3%, respectively [53]. MB, such as iron-MB, acts as a phosphorus fertilizer, increasing peanut yield by up to 33.2% under mulch films and boosting root morphology, chemical properties, and water retention [54]. MB has a large surface area, alkaline pH, and oxygen-containing groups, such as carboxyl, hydroxyl, and carbonyl. It increases the CEC, nutrient retention, and pH balance, especially in acidic or poor soils [55–60]. It also enhances microbial biomass, enzymatic activity, and overall soil health by influencing the soil C/N ratio. Microporosity, pH, and carbonates affect the α-diversity, leading to increased bacterial diversity and richness [40,61]. However, based on the source of the biochar, the types of organic molecules carried can lead to either enhanced fertility or toxicity if it is used in high concentrations. In fact, biochar toxicity occurs mainly at high concentrations, where it can disrupt soil nutrient balance, pH, and microbial activity, reducing plant growth and seed germination. A recent meta-analysis stated that fertility is related to the homogeneity of the specific molecular compounds of the organic matter, especially to the heterocyclic nitrogen compounds that can be present in biochar [62,63].

4.2. Adsorbent for Contaminant Removal

Biochar is widely applied in environmental rehabilitation, notably for remediating contaminated soils. Its vast surface area, porosity, negative charges, and oxygen-containing groups allow it to adsorb hazardous metals, including Pb, As, Cd, and Cr. Studies have shown that biochar reduces the bioavailability of metals, limiting plant uptake and pollution [64–66]. MB has many times the surface area, porosity, and chemical stability of biochar, making it an effective composite material for removing contaminants [10,67]. According to Oliveira, the application of biochar in the soil reduces the accumulation of Cd, Pb, Cu, and Zn in plant tissues by 38, 39, 25, and 17%, respectively [68]. Biochar derived from sources such as rice husk, corn straw, peanut straw, olive pomace, oak wood, and bark is highly suitable for the removal of heavy metals [69–73]. Iron-impregnated magnetic biochar has also shown promise in the removal of heavy metals like Cr (VI) when using zinc and chitosan-MB, and Pb (II), Cu (II), and Cd (II) when using $KMnO_4$-treated wood biochar [74,75]. Combining composite materials with biochar can enhance adsorption capacity for metals, metalloids, and organic pollutants, such as dyes and pesticides. For example, Wang et al. co-pyrolyzed soybean straw and rape straw with $Ca(OH)_2$, resulting in 49.85% and 61.91% Cd^{2+} adsorption, respectively, which were approximately 1.5 times higher than in the raw biochar [76]. In the past several years, carbon nano-biochar has been a valuable tool, owing to its distinctive properties and diverse applications across diverse fields, including energy, materials science, agriculture, and environmental management, particularly in terms of the phytoremediation of a wide range of organic, inorganic, and heavy metal pollutants [48,77–81]. Metal organic frameworks (MOFs) enhance the strength of these mechanisms by forming selective ligand–metal bonds and improving biochar structural stability [10,13,81–84]. Figure 2 illustrates an application and the mechanism for removing a contaminant using biochar.

Incorporating biochar into soil can sequester around 0.7–1.8 Gt CO_2 (C eq.) per year, and can ultimately reduce GHG emissions [85,86]. From a global perspective, biochar works as a driving force to increase crop yield by 11% and, at the same time, can reduce human-induced GHG emissions by 12% [60,87,88]. MB offers a critical climate change solution by increasing soil productivity, reducing GHG, and improving carbon storage at the same time [15,27,84]. The use of organic amendments, together with biochar, can increase the GWP_{100} by 26.1%, being antagonistic to CO_2, CH_4, and N_2O. The former factor, apart from its influence on the total carbon of the soil, includes texture and biochar feedstocks [89]. The adsorption capacity of materials partnered with biochar via their large surface areas aims to enhance carbon uptake, and at the same time, to capture nitrous oxide and methane gases [10,90].

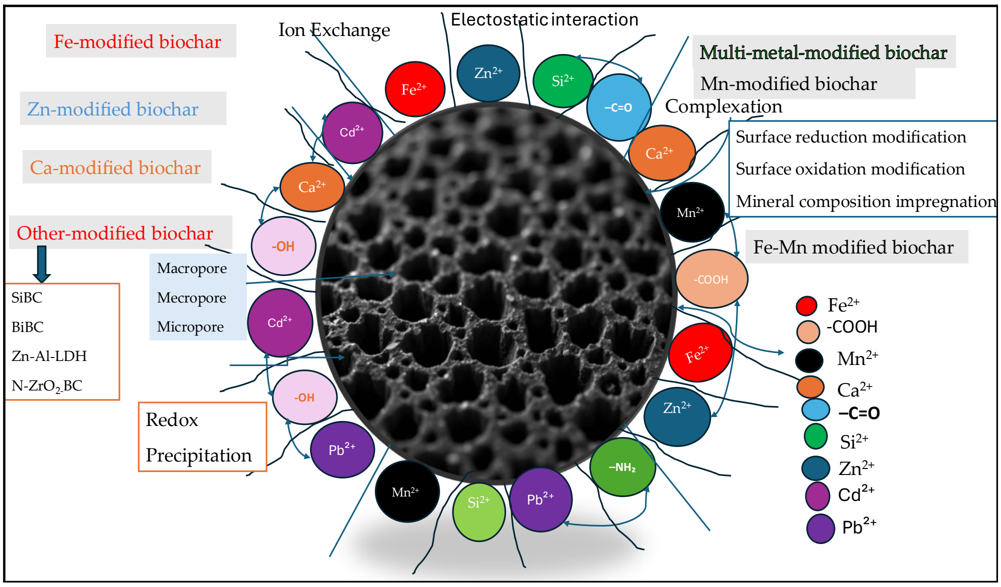

Figure 2. Mechanism of a contaminant adsorption using biochar.

4.3. Improvement in Crop Yield

In farmlands, biochar enhances crop productivity by improving soil quality and nutrients, boosting the water-holding capacity, and increasing the microbial population [91]. Its impacts on yields vary depending on factors such as soil type, feedstock, application rate, crop type, and climate [20]. A meta-analysis showed that the application of biochar increases the average yield by 16% [92]. Some studies have also shown that biochar increases the yield of rice by 28%, maize by 28%, wheat by 13.5%, soybean by 11%, and grapes by 66% [88,93,94]. Berihun reported that a 18 t ha^{-1} Lantana biochar application resulted in an increase in maize grain yield by 3% [95], while Maghsoodi showed a 67% increase in the yield of rice using 4 t ha^{-1} biochar [96]. Applications of 10, 25, and 50 t ha^{-1} poultry manure biochar in a radish field yielded an increase of 12% compared to the control [54]. Pandian (2016) reported that the application of 5 t ha^{-1} redgram stalk biochar increased dry groundnut and pod yields by 24% and 29%, respectively [97]. Milk tea waste-derived biochar, combined with 2% inorganic fertilizer, can enhance the growth parameters of wheat, including the chlorophyll content, root growth, and ultimately, yields [98]. Compared to organic manure, peanut yields were enhanced 22% by woodchip biochar, 23% (WBSC), and 18% (MBSC) in an Alfisol field trial utilizing 20 t ha^{-1} biochar [53]. Aguirre reported that the application of high-carbon biochar can increase dry corn yields by 84.58% per square meter [99]. According to Zhao, the application of biochar-based fertilizer can increase the yield of maize and Chinese cabbage by 86.99 g $plant^{-1}$ and 498.88 g $plant^{-1}$, respectively [100]. MB, such as iron-MB acts as a phosphorus fertilizer, increasing the yield of peanut 33.2% under film mulches [54]. The porosity and absorbency capacity of the biochar and the metal–organic frameworks play a significant role in ensuring nutrient use efficiency and minimizing nutrient leaching, which will increase the agricultural output. Additionally, they can enhance the sustainable nature of farming systems by reducing soil erosion and mitigating nutrient deficiencies [10,101]. Figure 3 illustrates the conceptual effects of biochar use on soil, plant growth, and crop yield.

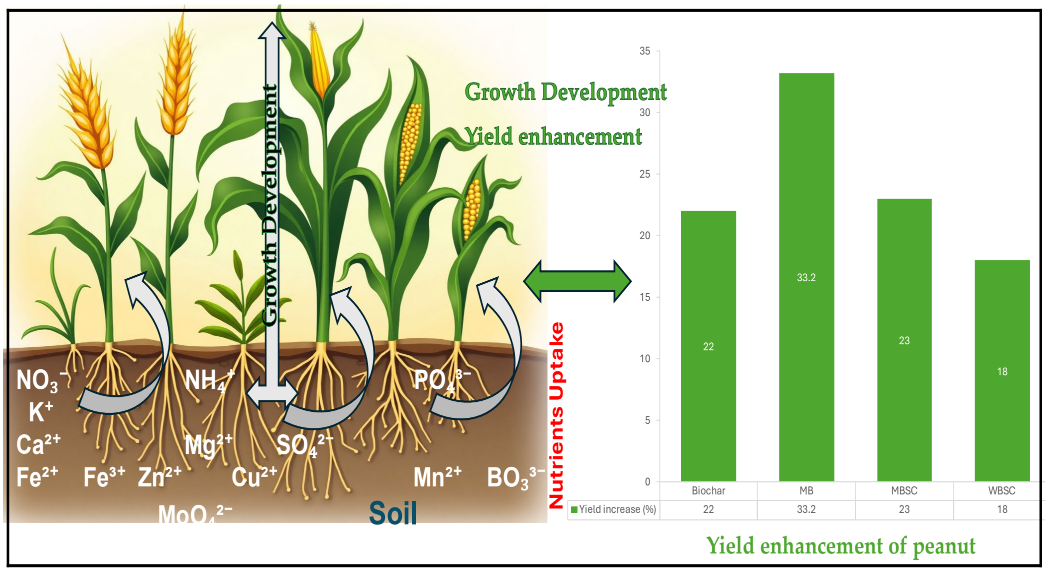

Figure 3. Conceptual illustration of biochar application effect on the soil and related plant development.

4.4. Economic Benefits

Aguirre reported that the application of high carbon (55%) biochar can increase corn yields by 55–80% over three years, generating a profit of EUR 8000 ha^{-1}. An investment of EUR 200 ha^{-1} can be doubled within three years [99]. Under a baseline scenario with biomass at 23.25 USD/green ton, stationary facilities produced 71% more biochar than needed in the Upper Peninsula and 10% more in the Lower Peninsula. Portable units fell short by 4% in the Upper Peninsula and 50% in the Lower Peninsula. While stationary units are more cost-effective and scalable, portable units can access a wider range of biomass and enable broader land applications. The prices of the biochar market worldwide are expected to increase to USD 3 billion by 2025 [102,103]. Through the normal process of creating biochar from farm byproducts, the efficiency of the soil increased by 15–25%, and waste management costs decreased by 30%. This leads to improved yields of crops, while, at the same time, reducing the application of chemical fertilizers [24]. The addition of MOFs to the matrices of charcoal can increase costs during implementation but improves their efficiency in adsorbing heavy metals and emerging pollutants from 50% to 80%. This provides a cheaper alternative to established wastewater treatment technologies [82,104]. Despite the high initial costs, the upscaling of MOF-based biochar composites can be lucrative owing to enhanced material reuse and longer service life; operational cost savings are foreseen to be as high as 40% in cases of industrial applications of pollutant remediation [105]. Table 1 summarizes the multifaceted impacts of biochar, its derivatives, and MB on soil properties, environmental remediation, agricultural productivity, climate change mitigation, and economics.

Table 1. Impacts of biochar and its MB derivatives on soil properties, environmental remediation, agricultural productivity, climate change mitigation, and economics.

Impact Area	Impacts of Biochar	Impacts of MB Derivatives	Details	References
Soil structure	+		Improves structure; porosity ↑ by 14–64%, bulk density ↓ by 3–31%	[48–50]
Water retention	+		20% biochar in sandy soil nearly doubles water retention, reduces erosion and loss	[48–50]
Soil fertility	+	+/−	Enhances fertility, though some organic molecules (e.g., heterocyclic N) may induce toxicity	[40,62,63]
Nutrient cycling (C/N, P)	+	+	Biochar: C/N ↑ by 20.9–33.8%, P ↑ by 14.7–23.5%; MB: C/N ↑ by 17.4–39.0%, P ↑ by 23.5–32.3%	[53]
Microbial biomass	+	+	Enhances microbial biomass, with low-grade nutrient-rich organics at low temperature	[40]
Enzymatic activity	+(3.7–5.5%)	++(6.4–10.1%)	Biochar increases activity; MB (biochar-compost mix) has a better impact	[53]
Hydrolase/non-hydrolase ratio	+(11.4–15.9%)	++(20.5–25.0%)	Enhances microbial metabolic processes	[53]
Soil microbial diversity (α-diversity)	+	+	Microporosity, pH, and carbonates boost diversity and richness	[40,61]
Microbial community shift	+		Basidiomycota ↑ and Actinobacteria ↓—benefits plant–beneficial fungi	[52]
Nitrogen cycling/emissions	+	+	Nitrification ↑ 40.8%, N_2O emissions ↓ 12.7%	[40]
Soil pH balance	+	+	Alkaline pH helps in acidic soils	[55–60]
CEC	+	+	Boosts nutrient retention capacity	[55–60]
Oil quality	−	+	Raw biochar: no effect; MB (WBSC/MBSC): ↑ oleic acid by 45%, ↓ linoleic acid by 79%	[53]
Crop yield (peanut)	±	+	MB (iron-MB) ↑ yield by up to 33.2% under mulching	[54]
Soil toxicity	−	−	Certain organic molecules in some biochar sources may cause toxicity	[62,63]
Surface area and porosity	+	++	Biochar: moderate; MB: higher than biochar	[10,67]
Heavy metal adsorption (Pb, Cd, Cr, As)	+	+	Biochar: effective *via* functional groups and surface area; MB: enhanced due to magnetic composites	[64–66,74–76]
Reduction of metal uptake in plants	+	+	Biochar: reduces Cd (38%), Pb (39%), Cu (25%), Zn (17%); MB: not explicitly quantified, but enhances uptake	[68]
Soil amendment and pollutant immobilization	+	+	Biochar: proven benefits; MB: improved when combined with MOFs or chitosan	[10,13,81–84]

Table 1. *Cont.*

Impact Area	Impacts of Biochar	Impacts of MB Derivatives	Details	References
Source-specific efficiency (rice husk)	+	++	Biochar: varies depending on feedstock; MB: enhances efficiency when used with modified biochar	[69–73]
Adsorption of organic pollutants (dyes, pesticides)	+	++	Biochar: moderate to effective; MB: more selective and stable with composites	[10,13,81–84]
Structural stability	+	+	Biochar: moderate; MB: improves *via* MOFs and chemical modifiers	[10,13,81–84]
Environmental safety	+/−	+/−	Biochar: generally safe; MB: requires more assessment for nanomaterials	[48,77–81]
Cost and scalability	−	+	Biochar: low-cost, scalable; MB: higher cost due to synthesis complexity	[10,67,81]
Ease of separation from environment	+	+	Biochar: low (non-magnetic); MB: easy separation due to magnetism	[74,75]
Synergy with phytoremediation	+	+	Biochar supports plant-based remediation; MB enhances through targeted contaminant removal	[48,77–81]
CO_2 Sequestration	+	+	Biochar sequesters up to 1.8 Gt CO_2 eq/year; MB enhances carbon stability through improving structure	[15,27,84–86]
Reduction in GHG Emissions	+	+	Biochar reduces human-induced GHG emissions by up to 12%; MB captures CH_4 and N_2O more effectively	[60,85–89]
CH_4 and N_2O adsorption Capacity	±	+	Biochar has limited adsorption; MB has higher GHG adsorption due to surface area and modifications	[10,85]
Long-term carbon storage	+	+	Both store carbon in stable forms; MB is more resistant to degradation	[15,27,84]
Global warming potential (GWP_{100}) when combined with organics	−	−	Combining with organic amendments may increase GWP by 26.1% due to CO_2, CH_4, and N_2O emissions	[10,90]
General crops	+		↑ 16% average yield increase using biochar	[92]
Rice	+		↑ 28% (biochar), ↑ 67% (biochar)	[89,93,96]
Maize	+	+	↑ 28% (biochar), +3% (Lantana biochar), ↑ 84.58% (dry yield), ↑ 86.99 g/plant (MB)	[89,93,95,99,100]
Wheat	+	+	↑ 13.5% (biochar), improves yield via milk tea biochar + 2% fertilizer	[89,93,98]
Soybean	+		↑ 11% (biochar)	[89,93]
Grapes	+		↑ 66% (biochar)	[94]
Radish	+		↑ 12% yield (poultry manure biochar)	[54]

Table 1. *Cont.*

Impact Area	Impacts of Biochar	Impacts of MB Derivatives	Details	References
Groundnut	+		↑ 24% dry yield, +29% pod yield (biochar)	[97]
Peanut	+	+	↑ 22% (woodchip biochar), +23% (WBSC), +18% (MBSC), +33.2% (iron-MB)	[53,54]
Corn	+		↑ 84.58% (biochar, dry yield)	[99]
Chinese cabbage		+	↑ 498.88 g/plant (MB fertilizer)	[100]
Crop yield improvement	+		↑ Biochar increases corn yields by 55–80% over 3 years	[24,99]
Profitability	+	+	↑ Biochar: EUR 8000 ha^{-1} profit; + MB-based: up to 40% operational savings in industrial use	[99,105]
Investment cost	−	−	Biochar: EUR 200 ha^{-1} initial investment; MOFs: high initial cost	[99,105]
Biochar production efficiency	+	−	Stationary units yield 10–71% surplus (biochar); portable units fall short 4–50% (biochar/MB)	[102,103]
Market growth potential	+	+	↑Biochar: USD 3B global market expected by 2025; ↑ MOFs: strong upscale market potential	[102,103, 105]
Soil efficiency	+		↑ Biochar improves soil by 15–25%; MOF impact not specified	[24]
Waste management cost reduction	+		↑ Biochar cuts waste management costs by 30%; MOF impact not specified	[24]
Pollutant adsorption efficiency	−	++	Biochar: basic adsorption; ↑ MOFs enhance removal from 50% to 80%	[82,104]
Operational cost savings (remediation)	−	+	Biochar: not specified; ↑ MOFs can reduce operational costs up to 40% in pollution treatment	[105]

Note: (+): positive impact, (++): strongly positive impact, (−): negative impact, (±): positive or negative impact depending on the material, (↑): increase, (↓): decrease.

5. Limitations, Challenges, and Future Directions

Although biochar is capable of making soil more fertile, increase its nutrient retention capacity, and is the best option for the environment, it still has problems. One of these problems is that the manipulation of pyrolysis conditions is complex, the quality of the feedstock is not uniform, and its performance in the field is not consistent. When biochar is applied, it can cause soil loss due to wind erosion, which disrupts the compact soil layer below. Biochar made from heavy metal-rich feedstocks can concentrate metals such as Cd, Pb, Zn, Cr, and Cu due to their non-volatility below 700 °C. For example, sewage sludge biochar may contain Cd (10–20 mg/kg), Zn (200–500 mg/kg), and Cu (100–300 mg/kg), highlighting the need for careful management [106]. Moreover, heavy metal accumulation in biochar can be a major concern, as they could be released over time. Repeated applications of biochar may also lower the survival rates of beneficial worms. The right amount of biochar depends on the type, texture, and fertility levels of the soil. Moreover, utilizing a feedstock containing a high content of heavy metals for the manufacture of biochar may not only be unprofitable but can also degrade soil health and productivity [107]. A comprehensive approach to biochar upgrading can be achieved by adjusting its characteristics through the incorporation of various materials in the field of materials science [87,108]. MOF-based biochar has been successfully utilized in the agricultural sector. This is a composite material known for its characteristics of high porosity, which makes it suitable for use as a carrier material for smart fertilizers with controlled nutrient release to improve nutrient use efficiency. MOF-biochar composites are highly effective in sequestering heavy metals such as Cd, Pb, and As, thereby curbing their propagation. Additionally, they facilitate nutrient cycling and promote soil health by supporting beneficial soil microorganisms and the effective growth of plants. The combination of these systems delivers climate mitigation through extended carbon storage and greenhouse gas reduction, as well as other environmental services. However, MOF-based biochar composites have not been adequately studied, necessitating extensive and long-term field investigations to confirm their environmental safety by assessing potential risks of leakage to plants and animals. Table 2 summarizes the limitations, challenges, and future research directions of biochar and its derivatives.

Table 2. Limitations, challenges, and future research directions of biochar and its derivatives.

Parameters	Short Description	References
Limitations	● Complex manipulation of pyrolysis conditions. ● The feedstock quality is inconsistent. ● Varied field performance. ● Risk for contaminants. ● Risk of wind erosion that leads to soil disturbance. ● Possible harm to soil organisms with excessive use. ● Not adequate for all types of soil and crops.	[24,107]
Challenges	○ Determination of appropriate application rates based on soil type, soil texture, and nutrient levels. ○ Risk of using feedstock with high heavy metal content, potentially degrading soil health. ○ Lack of long-term field data on newer technologies like MOF-biochar composites. ○ Ensuring long-term field performance and environmental safety. ○ Combination with recent agricultural systems. ○ Farmers' awareness and acceptance	[13,107]
Future directions	❖ Improvement of biochar qualities through the application of concepts of material science. ❖ Development of MOF-based biochar for controlled delivery of nutrients and intelligent fertilizers. ❖ Use of biochar to sequester heavy metals and assist soil microorganisms. ❖ Mechanistic research on biochar–soil–microbes interaction. ❖ Development of biochar for specific crops, climates, and contaminants. ❖ Safe reuse of waste biomass sources. ❖ Field trials for long-duration environmental impacts and crop yields.	[13,87,108]

6. Conclusions

Biochar and its derivatives significantly improve soil structure and fertility, potentially increasing porosity by 14–64%, reducing bulk density by 3–31%, and nearly doubling the water-holding capacity in sandy soils at a 20% application rate. Furthermore, biochar can enhance nutrient availability, stimulate microbial biomass, and, on average, increase crop yield by 16% and reduce CO_2 emissions by 8.62%. Additionally, it can reduce CH_4 emissions by 27%, N_2O emissions by 23.9%, and GHG emissions by 12%. Furthermore, biochar can sequester between 0.7 and 1.8 gigatons of CO_2 per year. MB, such as iron-amended biochar, can increase crop yields by over 30% and improve the root morphology, water-holding capacity, cation exchange capacity, and pH, especially in acidic soils. At the same time, it can increase microbial diversity and enzymatic activities, enhance carbon storage, reduce GHG emissions, and raise GWP_{100} by 26.1%. Biochar can also effectively adsorb heavy metals (Pb, Cd, As) and inhibit their bioavailability by up to 39%, and composites such as MOF-biochar can improve contaminant removal and regulate nutrient release. Iron-impregnated and composite biochar have demonstrated superior pollutant removal capability. In economic terms, biochar can significantly boost the profitability of crops and increase yield up to 80% with a potential profit of EUR 8000 ha^{-1} over three years. Additionally, it can reduce fertilizer demand and waste treatment costs by as much as 30%. Despite these advantages, limitations such as a lack of feedstock, complex pyrolysis procedures, land degradation, and negative impacts on beneficial soil microbes still exist. MB materials offer a sustainable approach by enhancing nutrient use efficiency, facilitating heavy metal immobilization, and stimulating beneficial microbial populations, thereby improving soil health and resilience to global change. New MB, particularly MOF composites, can be the key technology to counteract global climate change, water scarcity, famine, and food safety. Yet, further research in that direction is necessary to widen our knowledge and prevent new types of toxicity from emerging. Multidisciplinary research in this direction is essential to address current challenges and optimize MB applications in sustainable agriculture and environmental management.

Author Contributions: Conceptualization, A.S. and M.D.; methodology, A.S. and M.D.; software, M.M.H.; validation, A.S., B.K.S., and M.D.; formal analysis, M.M.H.; investigation, M.M.H.; resources, M.M.H.; data curation, A.S. and M.D.; writing—original draft preparation, M.M.H.; writing—review and editing, M.M.H., A.S., and M.D.; visualization, A.S., M.D., B.K.S., and M.M.H.; supervision, M.D. and A.S.; project administration, M.M.H. and M.D.; funding acquisition, M.M.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Program on Agricultural and Rural Transformation for Nutrition, Entrepreneurship and Resilience in Bangladesh (PARTNER)-APCU, BARC, Bangladesh Agricultural Research Council, New Airport Road, Farmgate, Dhaka-1215. Memo No: PARTNER/APCU-BARC 02/HRD/2024/673.

Acknowledgments: The authors are thankful for the support from the Agricultural and Rural Transformation for Nutrition, Entrepreneurship and Resilience in Bangladesh (PARTNER)-APCU, BARC, Bangladesh, for the PhD scholarship granted to Md. Muzammal Hoque. We also thank the Bangladesh Institute of Nuclear Agriculture (BINA), Mymensingh and DAFE, UNIBAS, Potenza, Italy.

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

Abbreviations

CEC	Cation exchange capacity
GHG	Greenhouse gas
HTC	Hydrothermal
MB	Modified biochar
MBSC	Maize biochar plus pig manure
MOF	Metal–organic framework
WBSC	Wheat biochar plus pig manure

References

1. Azad, N.; Behmanesh, J.; Rezaverdinejad, V.; Abbasi, F.; Navabian, M. An Analysis of Optimal Fertigation Implications in Different Soils on Reducing Environmental Impacts of Agricultural Nitrate Leaching. *Sci. Rep.* **2020**, *10*, 7797. [CrossRef] [PubMed]
2. Bai, J.; Song, J.; Chen, D.; Zhang, Z.; Yu, Q.; Ren, G.; Han, X.; Wang, X.; Ren, C.; Yang, G.; et al. Biochar Combined with N Fertilization and Straw Return in Wheat-Maize Agroecosystem: Key Practices to Enhance Crop Yields and Minimize Carbon and Nitrogen Footprints. *Agric. Ecosyst. Environ.* **2023**, *347*, 108366. [CrossRef]
3. Banik, C.; Bakshi, S.; Laird, D.A.; Smith, R.G.; Brown, R.C. Impact of Biochar-Based Slow-Release N-Fertilizers on Maize Growth and Nitrogen Recovery Efficiency. *J. Environ. Qual.* **2023**, *52*, 630–640. [CrossRef] [PubMed]
4. Pandian, K.; Vijayakumar, S.; Mustaffa, M.R.A.F.; Subramanian, P.; Chitraputhirapillai, S. Biochar—A Sustainable Soil Conditioner for Improving Soil Health, Crop Production and Environment under Changing Climate: A Review. *Front. Soil Sci.* **2024**, *4*, 1376159. [CrossRef]
5. Afshar, M.; Mofatteh, S. Biochar for a Sustainable Future: Environmentally Friendly Production and Diverse Applications. *Results Eng.* **2024**, *23*, 102433. [CrossRef]
6. Ahmad, M.; Lee, S.S.; Dou, X.; Mohan, D.; Sung, J.K.; Yang, J.E.; Ok, Y.S. Effects of Pyrolysis Temperature on Soybean Stover- and Peanut Shell-Derived Biochar Properties and TCE Adsorption in Water. *Bioresour. Technol.* **2012**, *118*, 536–544. [CrossRef]
7. Viotti, P.; Marzeddu, S.; Antonucci, A.; Décima, M.A.; Lovascio, P.; Tatti, F.; Boni, M.R. Biochar as Alternative Material for Heavy Metal Adsorption from Groundwaters: Lab-Scale (Column) Experiment Review. *Materials* **2024**, *17*, 809. [CrossRef]
8. Wang, J.; Xiong, Z.; Kuzyakov, Y. Biochar Stability in Soil: Meta-Analysis of Decomposition and Priming Effects. *GCB Bioenergy* **2016**, *8*, 512–523. [CrossRef]
9. Chagas, J.K.M.; de Figueiredo, C.C.; Ramos, M.L.G. Biochar Increases Soil Carbon Pools: Evidence from a Global Meta-Analysis. *J. Environ. Manag.* **2022**, *305*, 114403. [CrossRef]
10. dos Reis, R.A.; Fernández-Baldo, M.A.; Nunes, R.S.; Seabra, A.B. Metal-Organic Frameworks: An Overview of a Possible Solution for Modern Agriculture. *Microporous Mesoporous Mater.* **2025**, *391*, 113609. [CrossRef]
11. Vaz, R.C.A.; Lopez, M.A.R.; Ferreira, G.M.D. Unlocking the Potential of MOF-Biochar Composites: Advanced Functional Materials for Adsorption, Catalysis, and Energy Storage. *Mater. Today Chem.* **2024**, *42*, 102383. [CrossRef]
12. Tan, X.; Liu, Y.; Zeng, G.; Wang, X.; Hu, X.; Gu, Y.; Yang, Z. Application of Biochar for the Removal of Pollutants from Aqueous Solutions. *Chemosphere* **2015**, *125*, 70–85. [CrossRef] [PubMed]
13. Ghaedi, S.; Rajabi, H.; Hadi Mosleh, M.; Sedighi, M. MOF Biochar Composites for Environmental Protection and Pollution Control. *Bioresour. Technol.* **2025**, *418*, 131982. [CrossRef] [PubMed]
14. Rasheed, T.; Hassan, A.A.; Bilal, M.; Hussain, T.; Rizwan, K. Metal-Organic Frameworks-Based Adsorbents: A Review from Removal Perspective of Various Environmental Contaminants from Wastewater. *Chemosphere* **2020**, *259*, 127369. [CrossRef]
15. Ayaz, M.; Feizienė, D.; Tilvikienė, V.; Akhtar, K.; Stulpinaitė, U.; Iqbal, R. Biochar Role in the Sustainability of Agriculture and Environment. *Sustainability* **2021**, *13*, 1330. [CrossRef]
16. Al-Shammary, A.A.G.; Al-Shihmani, L.S.S.; Fernández-Gálvez, J.; Caballero-Calvo, A. Optimizing Sustainable Agriculture: A Comprehensive Review of Agronomic Practices and Their Impacts on Soil Attributes. *J. Environ. Manag.* **2024**, *364*, 121487. [CrossRef]
17. Glaser, B.; Haumaier, L.; Guggenberger, G.; Zech, W. The "Terra Preta" Phenomenon: A Model for Sustainable Agriculture in the Humid Tropics. *Naturwissenschaften* **2001**, *88*, 37–41. [CrossRef]
18. Glaser, B.; Lehmann, J.; Zech, W. Ameliorating Physical and Chemical Properties of Highly Weathered Soils in the Tropics with Charcoal—A Review. *Biol. Fertil. Soils* **2002**, *35*, 219–230. [CrossRef]
19. Sayre, L.B. The Pre-History of Soil Science: Jethro Tull, the Invention of the Seed Drill, and the Foundations of Modern Agriculture. *Phys. Chem. Earth* **2010**, *35*, 851–859. [CrossRef]
20. Jeffery, S.; Verheijen, F.G.A.; van der Velde, M.; Bastos, A.C. A Quantitative Review of the Effects of Biochar Application to Soils on Crop Productivity Using Meta-Analysis. *Agric. Ecosyst. Environ.* **2011**, *144*, 175–187. [CrossRef]
21. Lehmann, J.; Joseph, S. (Eds.) *Biochar for Environmental Management: Science, Technology and Implementation*; Taylor & Francis: Abingdon, UK, 2015. [CrossRef]
22. Beesley, L.; Moreno-Jiménez, E.; Gomez-Eyles, J.L.; Harris, E.; Robinson, B.; Sizmur, T. A Review of Biochars' Potential Role in the Remediation, Revegetation and Restoration of Contaminated Soils. *Environ. Pollut.* **2011**, *159*, 3269–3282. [CrossRef] [PubMed]
23. Mazarji, M.; Minkina, T.; Sushkova, S.; Mandzhieva, S.; Bayero, M.T.; Fedorenko, A.; Mahmoodi, N.M.; Sillanpää, M.; Bauer, T.; Soldatov, A. Metal-organic frameworks (MIL-101) decorated biochar as a highly efficient bio-based composite for immobilization of polycyclic aromatic hydrocarbons and copper in real contaminated soil. *J. Environ. Chem. Engineering* **2022**, *10*, 108821. [CrossRef]
24. Agrafioti, E.; Kalderis, D.; Diamadopoulos, E. Ca and Fe Modified Biochars as Adsorbents of Arsenic and Chromium in Aqueous Solutions. *J. Environ. Manag.* **2014**, *146*, 444–450. [CrossRef] [PubMed]

25. Chemerys, V.; Baltrėnaitė, E. *Modified Biochar: A Review on Modifications of Biochar Towards Its Enhanced Adsorptive Properties*; Environmental Protection Engineering: Vilnius, Lithuania, 2016.
26. Gupta, D.K.; Gupta, C.K.; Dubey, R.; Fagodiya, R.K.; Sharma, G.; Keerthika, A.; Mohamed, M.B.N.; Dev, R.; Shukla, A.K. Role of Biochar in Carbon Sequestration and Greenhouse Gas Mitigation. In *Biochar Applications in Agriculture and Environment Management*; Springer: Cham, Switherland, 2020; pp. 141–165. [CrossRef]
27. Novak, J.M.; Cantrell, K.B.; Watts, D.W.; Busscher, W.J.; Johnson, M.G. Designing Relevant Biochars as Soil Amendments Using Lignocellulosic-Based and Manure-Based Feedstocks. *J. Soils Sediments* **2014**, *14*, 330–343. [CrossRef]
28. Lin, Y.F.; Chen, J.L.; Baalousha, M.; Zhang, M.; Gao, B.; Varnoosfaderani, S.; Hebard, A.; Yao, Y.; Inyang, M.; Mahmoud, A.M.; et al. Preparation and Characterization of a Novel Magnetic Biochar for Arsenic Removal. *Bioresour. Technol.* **2009**, *24*, 2093–2101.
29. Han, M.; Zhang, J.; Zhang, L.; Wang, Z. Effect of Biochar Addition on Crop Yield, Water and Nitrogen Use Efficiency: A Meta-Analysis. *J. Clean. Prod.* **2023**, *420*, 138425. [CrossRef]
30. Martínez-Gómez, Á.; Poveda, J.; Escobar, C. Overview of the Use of Biochar from Main Cereals to Stimulate Plant Growth. *Front. Plant Sci.* **2022**, *13*, 912264. [CrossRef]
31. Tian, X.; Li, C.; Zhang, M.; Wan, Y.; Xie, Z.; Chen, B.; Li, W. Biochar Derived from Corn Straw Affected Availability and Distribution of Soil Nutrients and Cotton Yield. *PLoS ONE* **2018**, *13*, e0189924. [CrossRef]
32. Kowalska, A.; Manning, L. The Future of Food and Agriculture and Challenges. *Crit. Rev. Food Sci. Nutr.* **2020**, *61*, 1–180.
33. Yadav, S.K.; Bag, R. Effect of Bamboo Biochar on Strength and Water Retention Properties of Low Plastic Clay and Silty Sand. *Sci. Rep.* **2023**, *13*, 6201. [CrossRef]
34. Azeem, M.; Hayat, R.; Hussain, Q.; Ahmed, M.; Imran, M.; Crowley, D.E. Effect of Biochar Amendment on Soil Microbial Biomass, Abundance and Enzyme Activity in the Mash Bean Field. *J. Biodivers. Environ. Sci.* **2016**, *8*, 1–13.
35. Ighalo, J.O.; Ohoro, C.R.; Ojukwu, V.E.; Oniye, M.; Shaikh, W.A.; Biswas, J.K.; Seth, C.S.; Mohan, G.B.M.; Chandran, S.A.; Rangabhashiyam, S. Biochar for Ameliorating Soil Fertility and Microbial Diversity: From Production to Action of the Black Gold. *iScience* **2025**, *28*, 111524. [CrossRef] [PubMed]
36. Pradhan, S.; Parthasarathy, P.; Mackey, H.R.; Al-Ansari, T.; McKay, G. Food Waste Biochar: A Sustainable Solution for Agriculture Application and Soil–Water Remediation. *Carbon Res.* **2024**, *3*, 41. [CrossRef]
37. Zhou, D.; Liu, D.; Gao, F.; Li, M.; Luo, X. Effects of Biochar-Derived Sewage Sludge on Heavy Metal Adsorption and Immobilization in Soils. *Int. J. Environ. Res. Public Health* **2017**, *14*, 681. [CrossRef]
38. Kara, R.S.; Pazarlar, S.; Okur, B.; Almaz, C.; Okur, N.; Matula, S.; Miháliková, M. Texture and Contamination-Level Dependent Effects of Calcium-Rich Deinking Paper Sludge Biochar on Soil Cd Availability, Enzymatic Activity, and Plant Stress Mitigation. *Water. Air. Soil Pollut.* **2024**, *235*, 454. [CrossRef]
39. Gabhane, J.W.; Bhange, V.P.; Patil, P.D.; Bankar, S.T.; Kumar, S. Recent Trends in Biochar Production Methods and Its Application as a Soil Health Conditioner: A Review. *SN Appl. Sci.* **2020**, *2*, 1307. [CrossRef]
40. Li, X.; Wang, T.; Chang, S.X.; Jiang, X.; Song, Y. Biochar Increases Soil Microbial Biomass but Has Variable Effects on Microbial Diversity: A Meta-Analysis. *Sci. Total Environ.* **2020**, *749*, 141593. [CrossRef]
41. Liu, Z.; Niu, W.; Chu, H.; Zhou, T.; Niu, Z. Effect of the Carbonization Temperature on the Properties of Biochar Produced from the Pyrolysis of Crop Residues. *BioResources* **2018**, *13*, 3429–3446. [CrossRef]
42. Libra, J.A.; Ro, K.S.; Kammann, C.; Funke, A.; Berge, N.D.; Neubauer, Y.; Titirici, M.M.; Fühner, C.; Bens, O.; Kern, J.; et al. Hydrothermal Carbonization of Biomass Residuals: A Comparative Review of the Chemistry, Processes and Applications of Wet and Dry Pyrolysis. *Biofuels* **2011**, *2*, 89–124. [CrossRef]
43. Basu, P. Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory. In *Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory*; Academic Press: Cambridge, MA, USA, 2018; pp. 1–564. [CrossRef]
44. Knoef, H. (Ed.) *Handbook Biomass Gasification*, 2nd ed.; BTG Biomass Technology Group: Enschede, The Netherlands, 2012; ISBN 978-90-819385-0-1.
45. Antal, M.J. The Art, Science and Technology of Charcoal Production. *Ind. Eng. Chem. Res.* **2003**, *42*, 1619–1640. [CrossRef]
46. Chun, Y.; Lee, S.K.; Yoo, H.Y.; Kim, S.W. Recent Advancements in Biochar Production According to Feedstock Classification, Pyrolysis Conditions, and Applications: A Review. *BioResources* **2021**, *16*, 6512–6547. [CrossRef]
47. Thines, K.R.; Abdullah, E.C.; Mubarak, N.M.; Ruthiraan, M. Synthesis of Magnetic Biochar from Agricultural Waste Biomass to Enhancing Route for Waste Water and Polymer Application: A Review. *Renew. Sustain. Energy Rev.* **2017**, *67*, 257–276. [CrossRef]
48. Chausali, N.; Saxena, J.; Prasad, R. Nanobiochar and Biochar Based Nanocomposites: Advances and Applications. *J. Agric. Food Res.* **2021**, *5*, 100191. [CrossRef]
49. Chang, Y.; Rossi, L.; Zotarelli, L.; Gao, B.; Shahid, M.A.; Sarkhosh, A. Biochar Improves Soil Physical Characteristics and Strengthens Root Architecture in Muscadine Grape (*Vitis rotundifolia* L.). *Chem. Biol. Technol. Agric.* **2021**, *8*, 7. [CrossRef]
50. Sun, F.; Lu, S. Biochars Improve Aggregate Stability, Water Retention, and Pore-Space Properties of Clayey Soil. *J. Plant Nutr. Soil Sci.* **2014**, *177*, 26–33. [CrossRef]

51. Wang, C.; Luo, D.; Zhang, X.; Huang, R.; Cao, Y.; Liu, G.; Zhang, Y.; Wang, H. Biochar-Based Slow-Release of Fertilizers for Sustainable Agriculture: A Mini Review. *Environ. Sci. Ecotechnol.* **2022**, *10*, 100167. [CrossRef]
52. Lei, C.; Lu, T.; Qian, H.; Liu, Y. Machine Learning Models Reveal How Biochar Amendment Affects Soil Microbial Communities. *Biochar* **2023**, *5*, 89. [CrossRef]
53. Liu, C.; Shang, S.; Wang, C.; Tian, J.; Zhang, L.; Liu, X.; Bian, R.; He, Q.; Zhang, F.; Chen, L.; et al. Biochar Amendment Increases Peanut Production Through Improvement of the Extracellular Enzyme Activities and Microbial Community Composition in Replanted Field. *Plants* **2025**, *14*, 922. [CrossRef]
54. Luo, X.; Wang, D.; Liu, Y.; Qiu, Y.; Zheng, J.; Xia, G.; Elbeltagi, A.; Chi, D. Partial Substitution of Phosphorus Fertilizer with Iron-Modified Biochar Improves Root Morphology and Yield of Peanut under Film Mulching. *Front. Plant Sci.* **2024**, *15*, 1459751. [CrossRef]
55. Fakhar, A.; Galgo, S.J.C.; Canatoy, R.C.; Rafique, M.; Sarfraz, R.; Farooque, A.A.; Khan, M.I. Advancing Modified Biochar for Sustainable Agriculture: A Comprehensive Review on Characterization, Analysis, and Soil Performance. *Biochar* **2025**, *7*, 8. [CrossRef]
56. Lonappan, L.; Liu, Y.; Rouissi, T.; Brar, S.K.; Surampalli, R.Y. Development of Biochar-Based Green Functional Materials Using Organic Acids for Environmental Applications. *J. Clean. Prod.* **2020**, *244*, 118841. [CrossRef]
57. Uchimiya, M.; Bannon, D.I.; Wartelle, L.H. Retention of Heavy Metals by Carboxyl Functional Groups of Biochars in Small Arms Range Soil. *J. Agric. Food Chem.* **2012**, *60*, 1798–1809. [CrossRef] [PubMed]
58. Shen, Z.; Zhang, J.; Hou, D.; Tsang, D.C.W.; Ok, Y.S.; Alessi, D.S. Synthesis of MgO-Coated Corncob Biochar and Its Application in Lead Stabilization in a Soil Washing Residue. *Environ. Int.* **2019**, *122*, 357–362. [CrossRef] [PubMed]
59. Zhu, Z.; Zhang, Y.; Tao, W.; Zhang, X.; Xu, Z.; Xu, C. The Biological Effects of Biochar on Soil's Physical and Chemical Characteristics: A Review. *Sustainability* **2025**, *17*, 2214. [CrossRef]
60. Wang, J.; Wang, S. Preparation, Modification and Environmental Application of Biochar: A Review. *J. Clean. Prod.* **2019**, *227*, 1002–1022. [CrossRef]
61. Azadi, N.; Raiesi, F. Sugarcane Bagasse Biochar Modulates Metal and Salinity Stresses on Microbial Functions and Enzyme Activities in Saline Co-Contaminated Soils. *Appl. Soil Ecol.* **2021**, *167*, 104043. [CrossRef]
62. Drosos, M.; Orlando, M.; Cozzolino, V.; Scopa, A.; Piccolo, A. Deriving the Shannon Index from the Soil Molecular Humeome Serves as a Descriptor of Soil Organic Matter Stability under Different Cropping Systems. *Chem. Biol. Technol. Agric.* **2023**, *10*, 105. [CrossRef]
63. Sun, J.; Drosos, M.; Mazzei, P.; Savy, D.; Todisco, D.; Vinci, G.; Pan, G.; Piccolo, A. The Molecular Properties of Biochar Carbon Released in Dilute Acidic Solution and Its Effects on Maize Seed Germination. *Sci. Total Environ.* **2017**, *576*, 858–867. [CrossRef]
64. Jagadeesh, N.; Sundaram, B. Adsorption of Pollutants from Wastewater by Biochar: A Review. *J. Hazard. Mater. Adv.* **2023**, *9*, 100226. [CrossRef]
65. Tan, X.F.; Liu, Y.G.; Gu, Y.L.; Xu, Y.; Zeng, G.M.; Hu, X.J.; Liu, S.B.; Wang, X.; Liu, S.M.; Li, J. Biochar-Based Nano-Composites for the Decontamination of Wastewater: A Review. *Bioresour. Technol.* **2016**, *212*, 318–333. [CrossRef]
66. Majewska, M.; Hanaka, A. Biochar in the Bioremediation of Metal-Contaminated Soils. *Agronomy* **2025**, *15*, 273. [CrossRef]
67. Ghaedi, S.; Rajabi, H.; Hadi Mosleh, M.; Spencer, B.F.; Sedighi, M. Assessing the Efficiency and Reusability of Zirconium-Based MOF-Biochar Composite for the Removal of Pb (II) and Cd (II) in Single and Multi-Ionic Systems. *J. Environ. Manag.* **2025**, *380*, 125122. [CrossRef] [PubMed]
68. Oliveira, G.A.; Gevaerd, A.; Mangrich, A.S.; Marcolino-Junior, L.H.; Bergamini, M.F. Biochar Obtained from Spent Coffee Grounds: Evaluation of Adsorption Properties and Its Application in a Voltammetric Sensor for Lead (II) Ions. *Microchem. J.* **2021**, *165*, 106114. [CrossRef]
69. Chen, Z.S.; Liu, T.; Dong, J.F.; Chen, G.; Li, Z.; Zhou, J.L.; Chen, Z. Sustainable Application for Agriculture Using Biochar-Based Slow-Release Fertilizers: A Review. *ACS Sustain. Chem. Eng.* **2023**, *11*, 1–12. [CrossRef]
70. Jiang, X.; Denef, K.; Stewart, C.E.; Cotrufo, M.F. Controls and Dynamics of Biochar Decomposition and Soil Microbial Abundance, Composition, and Carbon Use Efficiency during Long-Term Biochar-Amended Soil Incubations. *Biol. Fertil. Soils* **2016**, *52*, 1–14. [CrossRef]
71. Lei, S.; Shi, Y.; Qiu, Y.; Che, L.; Xue, C. Performance and Mechanisms of Emerging Animal-Derived Biochars for Immobilization of Heavy Metals. *Sci. Total Environ.* **2019**, *646*, 1281–1289. [CrossRef]
72. Marcińczyk, M.; Krasucka, P.; Duan, W.; Pan, B.; Siatecka, A.; Oleszczuk, P. Ecotoxicological Characterization of Engineered Biochars Produced from Different Feedstock and Temperatures. *Sci. Total Environ.* **2023**, *861*, 160640. [CrossRef]
73. Meng, J.; Tao, M.; Wang, L.; Liu, X.; Xu, J. Changes in Heavy Metal Bioavailability and Speciation from a Pb-Zn Mining Soil Amended with Biochars from Co-Pyrolysis of Rice Straw and Swine Manure. *Sci. Total Environ.* **2018**, *633*, 300–307. [CrossRef]
74. Ni, B.J.; Huang, Q.S.; Wang, C.; Ni, T.Y.; Sun, J.; Wei, W. Competitive Adsorption of Heavy Metals in Aqueous Solution onto Biochar Derived from Anaerobically Digested Sludge. *Chemosphere* **2019**, *219*, 351–357. [CrossRef]

75. Shen, Y.; Zhang, N. Facile Synthesis of Porous Carbons from Silica-Rich Rice Husk Char for Volatile Organic Compounds (VOCs) Sorption. *Bioresour. Technol.* **2019**, *282*, 294–300. [CrossRef]
76. Wang, J.; Kang, Y.; Duan, H.; Zhou, Y.; Li, H.; Chen, S.; Tian, F.; Li, L.; Drosos, M.; Dong, C.; et al. Remediation of Cd2+ in Aqueous Systems by Alkali-Modified (Ca) Biochar and Quantitative Analysis of Its Mechanism. *Arab. J. Chem.* **2022**, *15*, 103750. [CrossRef]
77. Ahuja, L.R.; Green, T.R. Quantifying and Modeling Management Effects on Soil Properties. In *Modeling Processes and Their Interactions in Cropping Systems: Challenges for the 21st Century*; Wiley: Hoboken, NJ, USA, 2022; pp. 333–358. [CrossRef]
78. Weidner, E.; Karbassiyazdi, E.; Altaee, A.; Jesionowski, T.; Ciesielczyk, F. Hybrid Metal Oxide/Biochar Materials for Wastewater Treatment Technology: A Review. *ACS Omega* **2022**, *7*, 27062–27078. [CrossRef] [PubMed]
79. Trakal, L.; Michálková, Z.; Beesley, L.; Vítková, M.; Ouředníček, P.; Barceló, A.P.; Ettler, V.; Číhalová, S.; Komárek, M. AMOchar: Amorphous Manganese Oxide Coating of Biochar Improves Its Efficiency at Removing Metal(Loid)s from Aqueous Solutions. *Sci. Total Environ.* **2018**, *625*, 71–78. [CrossRef] [PubMed]
80. Rajput, V.D.; Minkina, T.; Ahmed, B.; Singh, V.K.; Mandzhieva, S.; Sushkova, S.; Bauer, T.; Verma, K.K.; Shan, S.; van Hullebusch, E.D.; et al. Nano-Biochar: A Novel Solution for Sustainable Agriculture and Environmental Remediation. *Environ. Res.* **2022**, *210*, 112891. [CrossRef]
81. Wang, P.; Chen, W.; Zhang, R.; Xing, Y. Enhanced Removal of Malachite Green Using Calcium-Functionalized Magnetic Biochar. *Int. J. Environ. Res. Public Health* **2022**, *19*, 3247. [CrossRef]
82. Ghaedi, S.; Rajabi, H.; Hadi Mosleh, M.; Babakhani, P.; Sedighi, M. UiO-67 Metal-Organic Framework Loaded on Hardwood Biochar for Sustainable Management of Environmental Boron Contaminations. *J. Environ. Chem. Eng.* **2024**, *12*, 114511. [CrossRef]
83. Laeim, H.; Molahalli, V.; Prajongthat, P.; Pattanaporkratana, A.; Pathak, G.; Phettong, B.; Hongkarnjanakul, N.; Chattham, N. Porosity Tunable Metal-Organic Framework (MOF)-Based Composites for Energy Storage Applications: Recent Progress. *Polymers* **2025**, *17*, 130. [CrossRef]
84. Mohan, B.; Sharma, H.K.; Ručman, S.; Singjai, P.; Pombeiro, A.J.L. Contaminants Removal and Monitoring: The Role of Hybrid MOFs in Agricultural Advancement and Soil Amendment. *Adv. Sustain. Syst.* **2024**, *9*, 2400637. [CrossRef]
85. Babu, S.; Singh, R.; Kumar, S.; Rathore, S.S.; Yadav, D.; Yadav, S.K.; Yadav, V.; Ansari, M.A.; Das, A.; Rajanna, G.A.; et al. Biochar Implications in Cleaner Agricultural Production and Environmental Sustainability. *Environ. Sci. Adv.* **2023**, *2*, 1042–1059. [CrossRef]
86. Sokolova, M.V.; Fath, B.D.; Buonocore, E.; Franzese, P.P. Assessment of Regulating Ecosystem Services Generated by Green Infrastructure: A Case Study of Bolzano, Italy. *Urban Clim.* **2025**, *60*, 102324. [CrossRef]
87. Woolf, D.; Amonette, J.E.; Street-Perrott, F.A.; Lehmann, J.; Joseph, S. Sustainable Biochar to Mitigate Global Climate Change. *Nat. Commun.* **2010**, *1*, 56. [CrossRef] [PubMed]
88. Liu, Q.; Zhang, Y.; Liu, B.; Amonette, J.E.; Lin, Z.; Liu, G.; Ambus, P.; Xie, Z. How Does Biochar Influence Soil N Cycle? A Meta-Analysis. *Plant Soil* **2018**, *426*, 211–225. [CrossRef]
89. Fu, J.; Zhou, X.; He, Y.; Liu, R.; Yao, Y.; Zhou, G.; Chen, H.; Zhou, L.; Fu, Y.; Bai, S.H. Co-Application of Biochar and Organic Amendments on Soil Greenhouse Gas Emissions: A Meta-Analysis. *Sci. Total Environ.* **2023**, *897*, 166171. [CrossRef] [PubMed]
90. Dai, X.; Wang, L.; Man, Z.; He, Y.; Wang, W.; Lin, F.; Zhu, J.; Liu, D.; Xiao, H.; Wang, K. In Situ Synthesis of Porous Metal-Organic Frameworks NH2-UiO-66 on Tea Stem Biochar and Application in Odours Adsorption. *Environ. Pollut.* **2024**, *353*, 124168. [CrossRef]
91. Knoblauch, C.; Priyadarshani, S.H.R.; Haefele, S.M.; Schröder, N.; Pfeiffer, E.M. Impact of Biochar on Nutrient Supply, Crop Yield and Microbial Respiration on Sandy Soils of Northern Germany. *Eur. J. Soil Sci.* **2021**, *72*, 1885–1901. [CrossRef]
92. Jiang, Y.; Li, T.; Xu, X.; Sun, J.; Pan, G.; Cheng, K. A Global Assessment of the Long-Term Effects of Biochar Application on Crop Yield. *Curr. Res. Environ. Sustain.* **2024**, *7*, 100247. [CrossRef]
93. Liao, J.; Liu, X.; Hu, A.; Song, H.; Chen, X.; Zhang, Z. Effects of Biochar-Based Controlled Release Nitrogen Fertilizer on Nitrogen-Use Efficiency of Oilseed Rape (*Brassica napus* L.). *Sci. Rep.* **2020**, *10*, 11063. [CrossRef]
94. Farhangi-Abriz, S.; Torabian, S.; Qin, R.; Noulas, C.; Lu, Y.; Gao, S. Biochar Effects on Yield of Cereal and Legume Crops Using Meta-Analysis. *Sci. Total Environ.* **2021**, *775*, 145869. [CrossRef]
95. Berihun, T.; Tolosa, S.; Tadele, M.; Kebede, F. Effect of Biochar Application on Growth of Garden Pea (*Pisum sativum* L.) in Acidic Soils of Bule Woreda Gedeo Zone Southern Ethiopia. *Int. J. Agron.* **2017**, *2017*, 6827323. [CrossRef]
96. Maghsoodi, M.R.; Najafi, N.; Reyhanitabar, A.; Oustan, S. Hydroxyapatite Nanorods, Hydrochar, Biochar, and Zeolite for Controlled-Release Urea Fertilizers. *Geoderma* **2020**, *379*, 114644. [CrossRef]
97. Pandian, K.; Subramaniayan, P.; Gnasekaran, P.; Chitraputhirapillai, S. Effect of Biochar Amendment on Soil Physical, Chemical and Biological Properties and Groundnut Yield in Rainfed Alfisol of Semi-Arid Tropics. *Arch. Agron. Soil Sci.* **2016**, *62*, 1293–1310. [CrossRef]
98. Sial, T.A.; Lan, Z.; Wang, L.; Zhao, Y.; Zhang, J.; Kumbhar, F.; Memon, M.; Lashari, M.S.; Shah, A.N. Effects of Different Biochars on Wheat Growth Parameters, Yield and Soil Fertility Status in a Silty Clay Loam Soil. *Molecules* **2019**, *24*, 1798. [CrossRef] [PubMed]

99. Aguirre, J.L.; González-Egido, S.; González-Lucas, M.; González-Pernas, F.M. Medium-Term Effects and Economic Analysis of Biochar Application in Three Mediterranean Crops. *Energies* **2023**, *16*, 4131. [CrossRef]
100. Zhao, H.; Xie, T.; Xiao, H.; Gao, M. Biochar-Based Fertilizer Improved Crop Yields and N Utilization Efficiency in a Maize–Chinese Cabbage Rotation System. *Agriculture* **2022**, *12*, 1030. [CrossRef]
101. Zhang, J.; Wang, S.; Cheng, X.; Chen, C.; Zhang, L.; Wang, Z. Design Strategies and Advantages of Metal-Organic Frameworks@ Lignocellulose-Based Composite Aerogel for CO2 Capture: A Review. *Sep. Purif. Technol.* **2025**, *356*, 129878. [CrossRef]
102. Singh, S.; Sivaram, N.; Nath, B.; Khan, N.A.; Singh, J.; Ramamurthy, P.C. Metal Organic Frameworks for Wastewater Treatment, Renewable Energy and Circular Economy Contributions. *NPJ Clean Water* **2024**, *7*, 124. [CrossRef]
103. Ahmed, N.N.; Pokharel, R.; Miesel, J.; Saffron, C.M. Assessing Feedstock Availability and Economic Feasibility of Utilizing Forest Biomass for Biochar Production in Stationary and Portable Systems in Michigan. *GCB Bioenergy* **2025**, *17*, e70030. [CrossRef]
104. Polyakov, V.; Bauer, T.; Kirichkov, M.; Butova, V.; Gritsai, M.; Minkina, T.; Soldatov, A.; Kravchenko, E. MOF-Biochar Nanocomposite for Sustainable Remediation of Contaminated Soil. *Environ. Sci. Pollut. Res.* **2025**, *32*, 5533–5550. [CrossRef]
105. Zhang, Y.; Hu, X.; Wang, H.; Li, J.; Fang, S.; Li, G. Magnetic Fe3O4/Bamboo-Based Activated Carbon/UiO-66 Composite as an Environmentally Friendly and Effective Adsorbent for Removal of Bisphenol A. *Chemosphere* **2023**, *340*, 139696. [CrossRef]
106. Méndez, A.; Gómez, A.; Paz-Ferreiro, J.; Gascó, G. Effects of Sewage Sludge Biochar on Plant Metal Availability after Application to a Mediterranean Soil. *Chemosphere* **2012**, *89*, 1354–1359. [CrossRef]
107. Tripathi, M.; Sahu, J.N.; Ganesan, P. Effect of Process Parameters on Production of Biochar from Biomass Waste through Pyrolysis: A Review. *Renew. Sustain. Energy Rev.* **2016**, *55*, 467–481. [CrossRef]
108. Shackley, S.; Hammond, J.; Gaunt, J.; Ibarrola, R. The Feasibility and Costs of Biochar Deployment in the UK. *Carbon Manag.* **2011**, *2*, 335–356. [CrossRef]