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Review

Characteristics and Applications of Biochar in Soil–Plant Systems: A Short Review of Benefits and Potential Drawbacks

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Abstract: The available literary data suggest the general applicability and benefits of different biochar products in various soil–plant–environment systems. Due to its high porosity, biochar might generally improve the physicochemical and biological properties of supplemented soils. Among the direct and indirect effects are (i) improved water-retention capacity, (ii) enhanced soil organic matter content, (iii) pH increase, (iv) better N and P availability, and (v) greater potential uptake of meso- and micronutrients. These are connected to the advantage of an enhanced soil oxygen content. The large porous surface area of biochar might indirectly protect the survival of microorganisms, while the adsorbed organic materials may improve the growth of both bacteria and fungi. On the other hand, N_2-fixing *Rhizobium* bacteria and P-mobilizing mycorrhiza fungi might respond negatively to biochar's application. In arid circumstances with limited water and nutrient availability, a synergistic positive effect was found in biochar–microbial combined applications. Biochar seems to be a valuable soil supplement if its application is connected with optimized soil–plant–environment conditions. This work aims to give a general review of the potential benefits and drawbacks of biochar application to soil, highlighting its impacts on the soil–plant–microbe system.

Keywords: Terra Preta; biochar; characterization; soil biology; symbiosis

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1. Introduction

The nearly one meter deep black soil of the Amazon River in South America is rich in carbon, calcium, magnesium, phosphorus, and trace elements. It is estimated that 10% of this area is covered by the so-called "black soil" or "Terra Preta" soil [1]. The main reason for its productivity is the dead biomass that has undergone thermal decomposition in an oxygen-free condition. The tropical climate can positively influence soil properties, transforming them in a favorable direction over time, without deleterious structural changes. Columbian soils with variable contents of biochar and different layers of carbon content are compared to control soils in Table 1. The fertile layers in those soils are much deeper (between 43 and 210 cm) than the 20 cm fertile layer in control soils nearby. The pH values in general are neutral or less acidic in comparison with the more acidic control soils without biochar amendment. Clay contents in these soils also tend to be greater, which could be related to the enhanced biological activity. The main reasons for the detected positive effects are the better aeration and improved water content of soils, as well as the indirect effects of greater microbiological abundance and activity, which might improve plant nutrition [2,3].

According to literary data, the Terra Preta soil is suitable for extracting carbon from the carbon cycle over a long period (centuries) and, in this way, the carbon-sequestration potential of soil can mitigate global warming [4]. The same effect was also realized in soils in which studied ancient biochar production. The carbon in these soils was sequestered and nutrients were absorbed for more than 30 years [5].

Terra Preta has served as a model for soil amendment and biochar industrial products are now used worldwide. During the preparation of biochar, the carbon content of mainly biomass-based feedstock materials is converted to aromatic carbon compounds and amorphous and graphitic-type structures during the process of so-called pyrolysis. By the end of the process, about 50% of the carbon content of the original biomass remains in the end-product. Still, this ratio is highly dependent on the conditions of the pyrolysis process [6]. The product created during such a carbonization process is referred to in the literature as "biochar," referring to its biological, natural bio-origin [7]. Varying the temperature and duration of pyrolysis can create significant differences in the properties of the biochar, even when starting from the same ingredient materials [8]. Three different fractions can be formed during the process. One is the *persistent* fraction, which remains largely resistant to further biological or chemical degradation for quite a long period [5,9]. This fraction typically has an amorphous structure that can contain graphite-like crystalline structures [10] consisting of conjugated aromatic structures to which many different functional groups are attached [11]. Toxic molecules (PAHs) also arise in this group of compounds, which must be considered at the point of application [12]. The *labile* fraction is the second characteristic group of substances. In the case of plant-derived biochar, it consists mainly of cellulose and hemicellulose which have not been converted during pyrolysis. When the pyrolysis process is fast, the carbonization is imperfect, which might result in an increase in the proportion of this group of substances. Once biochar is applied to the soil, this fraction is mineralized relatively quickly, in as little as a few weeks, and its nutrients are made available for crops [13–15]. The third fraction of biochar is the *ash* fraction, which is the oxidized residue of the mineral element in biomass. Its ratio increases with the pyrolysis temperature and the amount of oxygen involved in the process. A higher ash content increases the pH of the biochar and the concentrations of readily soluble elements present in a mineralized form [16]. Recognizing its beneficial effects, biochar production from various organic "wastes" and byproducts of agricultural and industrial origin has become a promising research area, and there are now a wide variety of related products and applications. Biochar is the umbrella term for products of biological origin, but we can also distinguish "pyrochar" and "hydrochar" products, depending on the production methodology and raw materials used, with industrial waste materials occasionally involved as well. Most examples of pyrochar and hydrochar, although also called "biochar", are not of biological origin (Figure 1).

Due to its phytonutrient composition, soil is suggested as the main application for biologically based biochar products, which are known to have significant amounts of humic and fulvic acids attached to their porous structure surfaces [17].

Table 1. Main physicochemical properties of the Columbian "Terra Preta" and similar non-biochar-affected control soils [18,19].

Site	Soil	Fertile Layer (cm)	Age (year)	Clay (%)	pH	Carbon (mg g^{-1})	Nitrogen (mg g^{-1})	C:N Ratio
Hatahara	Terra Preta	43–69	600–1000	27.0	6.4	22.0	1.0	22
	Control	0–10	600–1000	35.9	4.6	21.8	1.6	14
Lago Grande	Terra Preta	0–16	900–1100	22.6	5.9	31.5	1.8	18
	Control	0–8	900–1100	26.7	4.2	17.5	1.3	13
Acutuba	Terra Preta	48–83	2000–3000	10.4	5.6	15.7	1.0	16
	Control	0–30	2000–3000	8.5	4.7	15.4	0.8	19
Dona Stella	Terra Preta	190–210	6700–8700	0.3	5.0	16.5	1.1	15
	Control	0–12	6700–8700	0.3	3.9	10.2	0.4	26

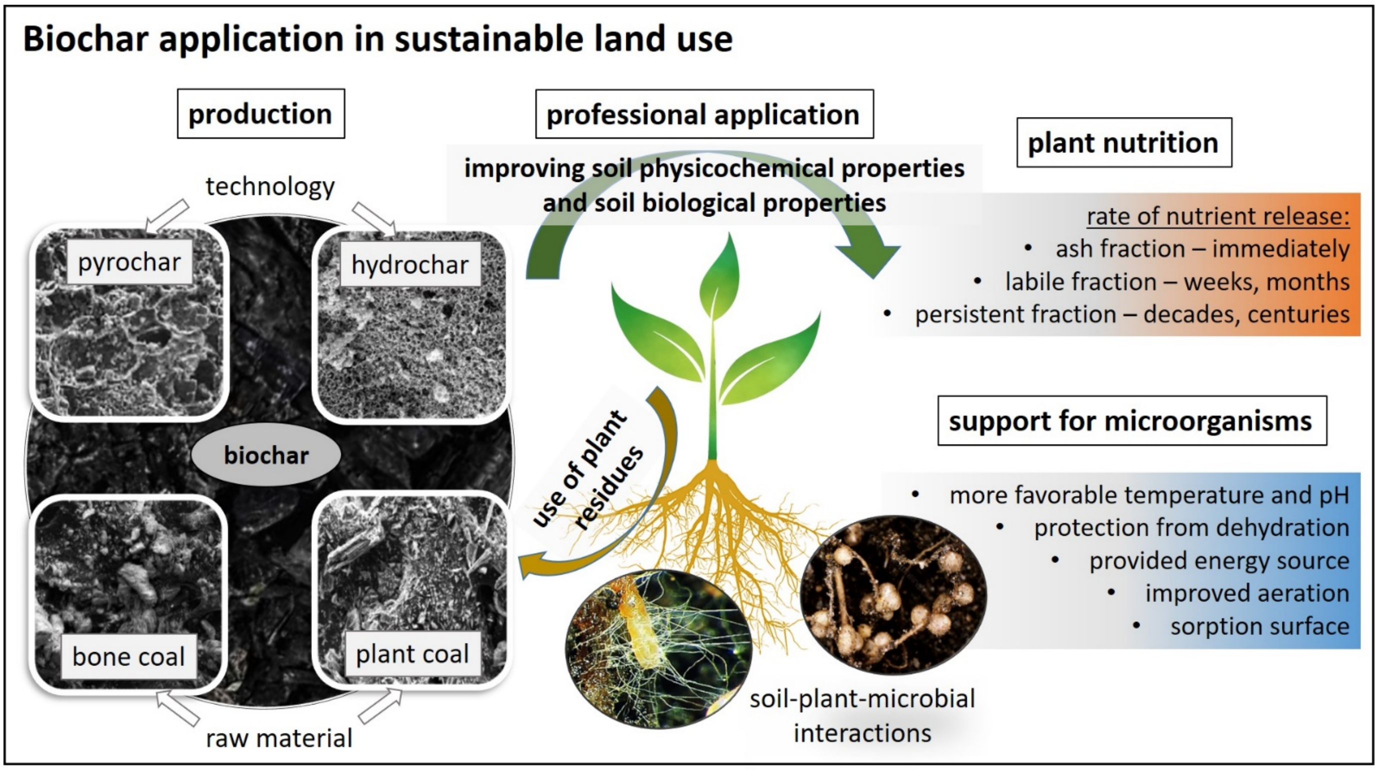

Figure 1. Main types of biochar and their agricultural uses.

The question arises as to whether the effects of biochar are beneficial in all cases for the soil–plant–microbial relationship; are there any time and quantity limits to biochar application? Furthermore, what are the most influential soil-environmental factors for its application? Do the effects appear directly through the physicochemical properties of the soils or indirectly in the soil–plant microbial system? The purpose of this summary is to review the general aspects (benefits and some drawbacks) of biochar application that might support its proper use in variable soil-environmental conditions, particularly to support the better growth of plants.

2. Approach to the Concept and Production of Biochar

Biochar is a substance formed via the reductive pyrolysis of high-carbon-containing dead plant and/or animal biomass (heated oxygen-free at high temperatures). Its structural properties strongly depend on the organic materials used for the reductive "burn", formation temperature, and duration of action, i.e., the production conditions. The literature distinguishes two major groups of production processes in terms of the initial raw materials:

1. Biochar produced a relatively low (450–550 °C) pyrolyzing temperature, most often produced with high carbon-content substances according to the literature. It is mainly capable of long-term binding of groundwater and dissolved ions, and usually originating from plant residues, byproducts, and/or animal manures.
2. Biochar produced from animal bones at high temperatures (600–650 °C or higher) with a high calcium phosphate content, along with apatite minerals with significantly lower carbon contents.

In addition to biochar, oils and various synthesis gases are also generated during pyrolysis (Table 2). However, their exact proportions in the final products may vary as a function of the raw materials and production methods.

"Terra Preta" soil is well supplied with both organic matter and minerals, the most important of which are nitrogen, phosphorus, and potassium (NPP macronutrients) (Table 1). There are both direct and indirect reasons for this. In biochar production, plant waste and animal manure are mainly used, and the final product's composition is proportional to the initial concentrations of raw materials. Its morphology is closely related to pore development, as well as to the shapes of pores. The smaller the pores, the larger the biochar surface area in general [22]. Biochar can show some variability in morphological structures when different initial feedstocks are used (Figure 2).

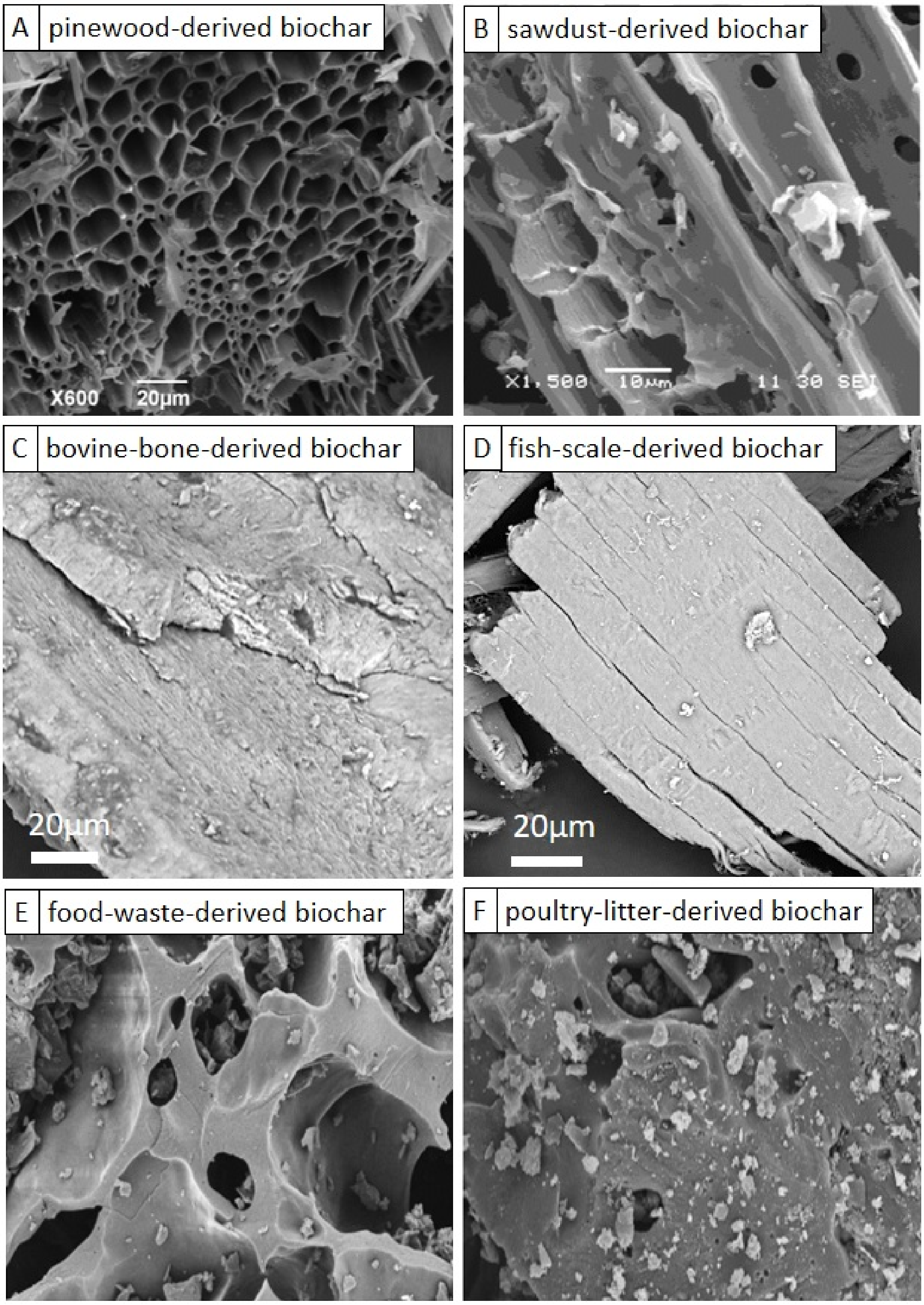

Figure 2. Surface morphology of some biochar, based on the different feedstocks [22–26]. (**A**) pinewood-derived, (**B**) sawdust-derived, (**C**) bovine-bone-derived, (**D**) fish-scale-derived, (**E**) food-waste-derived, (**F**) poultry-litter-derived biochar.

Table 2. The products of initial feedstock mass under selected pyrolysis conditions [20,21].

Method of Pyrolysis	Liquid (Bio-Oil, Bio-Fuel)	Solid (Biochar)	Gas (Synthesis Gas, Bio-Gas)
Moderate temperature (~500 °C), short hot vapor residence time (<2 s)	75% (25% water)	12%	13%
Moderate temperature (<500 °C), moderate hot vapor residence time (10–20 s)	50% (50% water)	20%	30%
Slow temperature (~400 °C), very long solid residence time	30% (70% water)	35%	35%
High temperature (>800 °C), long vapor residence time	5% tar	10%	85%

3. Physicochemical Properties of Soils Affected by Biochar

When mixed with soil, biochar can change the soil's texture, pore size distribution, and bulk density, positively affecting the aeration and the water-holding capacity [29–31]. The final soil characteristics following biochar addition are highly dependent on the initial quality of the soil, and its type and composition (porosity) in general. The application of biochar can serve first to improve the soil physical status, which may through several indirect effects affect other soil chemical and biological characteristics. In clayey soils, for instance, a larger pore size can be suggested (larger than the main pores of the clay, as 10 nm in diameter) in order to increase the aeration of these rather compacted soils. The opposite is possible in soils with high sand contents, where biochar can be used to improve the water-holding capacity and nutrient adsorption, not aeration. The variability of the porous structure of biochar, therefore, can increase the amount of water stored and the size and distribution of minerals as soil formers [32]. Biochar can have a surface area of up to 800–5000 mm^2 per gram, and this porous, airy structure indirectly contributes to a generally high microbial activity and surviving ability. This beneficial property of biochar is also exploited in contaminated soils where environmental (stress) conditions (air limitations, lack of nutrients, critically low temperatures) would otherwise impede the remediation processes, such as the degradation of antifreeze propylene glycol [33]. Meanwhile, in the case of other forms of pollution, the positive effect of biochar on soil porosity is highlighted. Still, microorganism habitats and the protective surface (for biofilm production) provided for microorganisms are also a key issue in many soils, especially colloid-poor sandy soils [33,34].

Biochar has a liming effect [35] and increases soil cation exchange capacity by raising the pH, influencing the availability of nutrients, and thus preventing their leaching [36,37]. For example, the availability of phosphate, iron, boron, zinc, and manganese has been shown to decrease at high pH [37]. Increasing pH also increases microbial nitrification, which results in losses of nitrate and limited availability of ammonium, the preferred nitrogen source for plants [38]. In this way, in some cases, the pH-raising effect of biochar can create unfavorable conditions for plants, particularly in calcareous soils; this can result in yield losses [38,39]. Biochar has its own nutrient content (Table 3); depending on the raw material used and the pyrolysis temperature, it may contain large amounts of macro- and micronutrients with different levels of availability [40]. Therefore, biochar can be directly involved in the nutrient replenishment of plants [41]; however, aging, oxidation, and microbial degradation can alter the surface functional groups and chemical structures of biochar, with the result that the sorption capacity of biochar generally decreases with time. The effect of the aging, oxidation, or microbial degradation of biochar-derived dissolved organic matter on pollutants and the soil environment over time is still unclear [42]. In biochar, nutrients can be present in three forms, depending on the production conditions and the rate of utilization, as mentioned above. The nutrients in the ash fraction can be taken up over short periods by plants, particularly in well-watered soils, resulting in known benefits for plant growth. Nutrients in the labile fraction become available only after a few weeks of mineralization, as a consequence of the enhanced soil's biological activity. Nutrients incorporated into the bodies of microorganisms become unavailable for a certain period, which may produce competition for nutrients between plants and microorganisms. This fact can result a so-called pentozan effect, which can develop in soils with very low nitrogen content but which are high in degradable organic materials (e.g., wheat straw) [43]. The nutrients in the persistent fraction of biochar are only released decades or centuries later, as discussed earlier [9]. These fractions can all play a role in the direct nutrient supply of plants.

Table 3. Chemical constituents of biochar produced from various feedstock sources under different production temperatures (based on Jatav et al., 2021 [44]).

Raw Material	Production (°C)	pH	C g kg^{-1}	N g kg^{-1}	C:N Ratio	P g kg^{-1}	K g kg^{-1}	Literature
Green waste	450	6.2	680	1.7	400	0.2	1	Chan et al., 2007 [45]
Poultry litter	450	9.9	380	20	19	25	22	Chan et al., 2007 [45]
Residue (*Zea mays*)	350		675	9.3	73		10.4	Nguyen and Lehmann, 2009 [46]
Residue (*Zea mays*)	600		790	9.2	86		6.7	Nguyen and Lehmann, 2009 [46]
Peanut shell (*Arachis hypogaea*)	400		499	11	45	0.6	6.2	Margini-Bair et al., 2009 [47]
Rice husk	370–550	8.5	470	5.9	80	1.03	7.9	Prakongkep et al., 2014 [48]
Wood (*Quercus ilex*)	400	9.9	676	5.3	128		3.2	Forján et al., 2014 [49]
Pine wood (*Pinus* spp.)	~480	8.4	532	3.7	143		9.4	Yargicoglu et al., 2015 [50]
Wood (*Quercus* spp.)	400	6.9	427	3.3	130	0.6	3.8	Zhang et al., 2015 [51]
Wood (*Quercus* spp.)	600	9.5	455	4.1	111	0.6	4.4	Zhang et al., 2015 [51]

An example of the direct, rapid nutrient replenishment of biochar was described by Angst et al. in 2013 [41]. In their study, the magnitude and dynamics of short-term phosphorus (P), magnesium (Mg), and potassium (K) release were assessed through repeated cold-water extraction using hardwood biochar (*Acer pseudoplatanus*). The feedstock was converted in a traditional charcoal ring furnace with a holding time of 24 h and a peak temperature of approximately 500 °C. The proximate analysis results for the char of volatiles, fixed carbon, and ash were 18.5%, 77.0%, and 4.4%, respectively. The carbon, hydrogen, oxygen, nitrogen, and sulfur contents were 746, 28, 178, 4.0, and 0.2 mg kg^{-1}, respectively. The phosphorus concentration in the biochar (119 mg kg^{-1}) was approximately four times greater than that in the *Acer* spp. feedstock, reflecting the ratio of feedstock mass to biochar yield in biochar production. In contrast, the Mg and K contents of 1889 and 3309 mg kg^{-1} were twice those of the feedstock. Approximately 30–103% of the total P, 6–27% of the total Mg, and 82–122% of the total K were leached from the biochar.

Increased nutrient retention is a vital element of harmonious nutrient supply. Biochar soil treatment significantly reduces the leaching of nutrients from organic and inorganic fertilizers [52]. In their nutrient leaching experiment in 2020, Laird et al. [53] significantly reduced the N, P, Mg, and Si contents of water-leached clay soils treated with organic manure. In summary, the beneficial effects of biochar on the soil's ability to provide nutrients to plants stem from the following factors: (1) readily soluble nutrients brought into the soil [15] and nutrients from the mineralization of the labile fraction [13–15]; (2) reduced leaching due to biochar's high cation exchange capacity [54,55]; (3) the reduction of ammonia volatilization and lower N loss due to the removal of N_2 and N_2O emissions from denitrification [56,57]; and (4) N, P, and S retention due to increased biological activity [58,59]. It is important to note that some of the above processes are inseparable from soil biological functions.

Adding biochar creates a darker soil surface, which increases the soil temperature, thus increasing the microbial biomass and activity values, which is also a positive factor [58]. The effects on the improvement of light absorption capacity and the increase of soil temperature can be efficiently utilized in the agricultural practices of boreal countries. Biochar usage can thus extend, for example, the northern border of wheat and maize cultivation [59].

4. Biological Properties of Soils Affected by Biochar

Several studies have reported beneficial effects of biochar substances—artificially created by charring biological waste and byproducts—on soil productivity in terms of increasing biological activity and the sequestration of greenhouse gases (GHGs) [60–62]. Among GHGs, the reduction of nitrous oxide (N_2O) and methane (CH_4) has been highlighted [54,57,62], but carbon sequestration (C) is also a critical property [52]. Biochar as a substance is mainly recommended for acidic soils as it alkalizes the pH and improves nutrient retention through cation adsorption, thereby benefiting soil productivity (Table 3). However, the variety of experiments and sites described in the literature make it difficult to summarize the effects on soil biomass and draw appropriate conclusions. In many cases, the results are contradictory and highlight only one factor of a multifactor system. The conditions for applying biochar depend on the properties of the soil, environmental conditions, raw material, dose, and many other biotic and abiotic factors. Its usage can lead to changes in soil biotic communities that are of interest but also of concern. In the quantitative development of the microbial community, not only plant-growth-promoting rhizobacteria (PGPR), which are favorable for cultivation, but also soil-borne pathogens may potentially multiply [63,64]. From the point of view of soil protection, such research is important, as the microbiological communities of soil affect both its functions and ecosystem services [65–67]. The properties that affect functionality are structure and stability, aeration, nutrient cycling, water balance, and the already mentioned carbon sequestration [68]. This refers to soils' suppressive or receptive properties against pathogens, to which biochar can contribute in both positive and negative ways.

Overall, increased microbial biomass following biochar supplementation has been determined with various soil-testing methods. The most widely known of these are molecular nucleic-acid-based techniques [69,70], breeding, and/or the classical colony-counting method [64,71], substrate-induced respiration [72–74], fumigation extraction [74], phospholipid fatty acid (PLFA) analysis [70], and microscopic examination of staining particles [75–77]. In addition, Tian et al. in 2016 [78] and Wang et al. in 2020 [79] found that microbial reproduction rates also increased in biochar-treated soils. The increased microbial activity was further reflected in the CH_4 formed during biodegradation after biochar addition. An increase was observed in the number of anaerobic and cellulose-degrading bacteria as an indirect effect. Thus, there may be a wide variety of microbes, of different types and functions in terms of plant production and protection, food quality, and safety, within each physiological group. The magnitude of these changes differs from species to species and even between strains [12]. Their increasing mass is a common phenomenon with biochar, but its extent and possible maximum are strongly determined by the ecophysiological properties of the studied taxon [80–82]. This has also been observed in stress-laden saline soils [83].

Biochar, like high-carbon sugars, immobilizes the easily absorbed nitrogen content of the soil and can thus be a successful tool in environmental restoration efforts [84]. In soil–plant systems, the microbiological properties of the rhizosphere have been mainly studied, as is shown in Table 4. Rékási et al. in 2010 [85] and Javeed et al. in 2019 [86] found that biochar delivered to the rhizosphere increases the number of microbes compared to that in undisturbed/untreated soil. However, generalization is prevented by the fact that Graber et al. [87] reported the opposite in 2010, referring to the strong dose-dependence of the application. Regarding microsymbionts, the presence and biomass of the two most common, arbuscular (AM) and ectomycorrhiza (EM), have also been shown to be positively influenced by the presence of biochar [75,76,83]. Both the rate of ectomycorrhizal formation and the level of root colonization increased (by 157%) at the roots of larch (*Larix gmelinii*) seedlings [80]. The AM colonization increased by 40% in a wheat rhizosphere two years after biochar application, while a 6% increase in mycorrhizal colonization was observed with 6 t ha^{-1} of biochar added to tree plantations [81]. However, we do not know how and to what extent the number of fungi and the extraradical hyphae mass extending beyond the root were affected by the added biochar. This is because the porous biochar can protect against physical damage resulting from soil compaction or a change to the nutrition of the soil fauna through its internal pores. Therefore, the actual surface protection of the microorganisms inside, consistent with their susceptibility to dehydration, is a critical issue in biochar treatment [12].

It has already been mentioned that one of the beneficial effects of biochar is on the surface binding of the gases produced in the soil, such as CO_2. These indirect mechanisms influence the microbiological activity of soils and the composition of microbial groups [14,25,36,48,55]. However, the result is highly quality-dependent. In 2019, Rizwan [88] found that the properties of the hydrocarbon produced via the hydrothermal pathway differ significantly from the pyrolyzed version. On one hand, some authors have proposed that hydrothermal carbon better stimulates the germination and colonization of AM fungal spores in the soil due to its higher water content. On the other hand, other authors suggest that AM fungal colonization in hydrothermal char may decrease due to the improved physicochemical soil condition, which ultimately makes symbiosis unnecessary [88,89]. Decreased AM symbiosis has been observed with the use of high-phosphorus bone-derived biochar [90–92]. Thus, the essential role of beneficial mycorrhizal fungi that provide live, direct contact (their well-known properties that improve uptake of phosphorus and other elements, or even their stress-buffering capabilities) may be triggered by the use of various biochar products.

The direct adverse effects of biochar can even be demonstrated in soils with high salt or heavy metal contents, which inhibit the formation and function of the rhizosphere connection due to their poor chemical properties [93–95]. Depending on the surface and porosity of the biochar, it can bind not only the contaminants but also the organic nutrients essential for plant nutrition. The absence of these nutrients is of paramount importance in stress-laden soils [96,97]. In summary, biochar reduces the mutual efficiency of the plant–microbe system, which is an essential element of cooperation and symbiosis. According to previous results, in the absence of biochar, an improvement can be observed in the symbiotic relationships within soils contaminated with saline or heavy metals due to environmental stress [98,99]. In addition, biochar must be applied while considering the sensitivity of the symbiont relationship, which is why it should only be used with the appropriate expertise.

The beneficial effect of biochar can also be reduced by overwhelming the nutrient availability caused by the addition of fertilizer, which can indirectly reduce the growth rates of microbes [16,82,90]. Improvement in AM colonization was observed only with the smallest amount of "starter" fertilizer application [83]. According to Biró in 2000 [101], the nitrogen dose capable of promoting symbiosis in a low (1.5%) soil content corresponded to 45 kg ha^{-1} of nitrogen fertilizer and only 120 kg ha^{-1} of phosphorus. Even higher fertilizer doses caused multiple declines in symbiont functionality and economical biological N_2 binding. The nutrient uptake effect of mycorrhizal fungi was reduced mainly by phosphorus-containing fertilizers but not by nitrogen-containing fertilizers [101]. In the initial development stage of pulse crops, when studying the nitrogen-binding *Rhizobium* bacteria capable of symbiotic contact, Ogawa and Okimori in 2010 [102] found the opposite result. With the addition of nitrogen and phosphorus fertilizer, symbiosis did not develop, or if it did, it was later downsized by the plant. In the existing symbiosis, the richness of the arbusculum that signals and ensures functioning can drop or re-emerge in as little as eight days, depending on the plant's needs [83].

Table 4. Summary of possible mechanisms by which microbial abundance is affected by biochar supplementation of soil. (Original data from Lehmann et al., 2011 [100], were refreshed based on new results).

Mechanism	*Rhizobium*	Bacteria	Mycorrhiza	Filamentous Fungi
Protecting surface	0	+	+	+
Improved hydration	+	+	+	+
N availability	−	+	0	+
P, Ca, Mg, K availability	+	+	−	−
Micronutrient availability	+	+	−	+
pH increase	+	+	0	0
pH decrease	−	−	0	0
Sorption of microorganisms	−	+	+	+
Biofilm formation	+	+	0	0
Sorption of dissolved organic matter as an energy source for microorganisms	0	+	0	+

+ positive effect, − negative effect, 0 no change.

Under the same environmental conditions, the development of microbial biomass shows an increasing tendency to rise in the range from pH 3.7 to pH 8.3 [68,103,104]. However, fungi and bacteria react differently to changes in pH value. For example, the number of bacteria increases at around pH 7, while the fungal biomass does not change significantly at such neutral values [104]. A similar result was observed in *Rhizobium*-inoculated pulse crops [101,105]. Depending on the biochar raw material, its production temperature, and the amount applied, the soil's acidity could be less than 4 or its alkalinity could be more than 12 [21,39,58,73]. The degree of biochar oxidation after entry into the soil plays an essential role in this process [7,11,14,72].

In summary, both the physicochemical adsorption properties of biochar (direct effect) and the mineralization due to microorganisms settling in more significant amounts in the pores of the biochar (indirect effect) contribute to an increase in plant nutrient uptake. Thus, the use of biochar does not inhibit but rather aids natural soil biological processes, which will allow the combined use of biochar and microbiological inoculants (biofertilizers, plant conditioners, other agents) in crop production in the future [38,50,52,60,69].

5. Soil Productivity Effects of Biochar

Most research results to date have confirmed biochar's beneficial effect for increasing soil productivity, which is known as the most important soil function. The authors indicated a growth-inducing effect of biochar yield in almost 90% of the reviewed studies. The processed scientific publications reported yield increases of between 20% and 220% in proportion to the quantity and quality of biochar used. Some authors [106] considered only biochar application to intensive arable crops, and there were therefore no data available from settings such as organic farming areas. In an earlier study, Major [107] examined the increase and nutrient replenishment of a maize yield with soya sowing. Plant–coal biochar was applied at 8 and 20 t ha^{-1}. The yield did not increase in the first year, but 28%, 30%, and 140% improvements were found in pots after applying a 20 t ha^{-1} dose in the following years. The effect was attributed to the better nutrient uptake, mainly via the soil's 77–320% higher Ca and Mg contents in biochar-treated plots. At the same time, a more moderate increase in yield in the later years indicated a dose effect and the shortcomings of our current knowledge, which draws attention to the importance of long-term studies and the need for continuous field experiments and soil monitoring. Table 5 shows a summary of possible mechanisms by which physical, chemical, and biological properties can be affected by biochar supplementation in soil.

Table 5. Summary of possible advantages and disadvantages of biochar application in various soil–plant systems with suggested solutions.

Soil Characteristics	Advantages of BC	Disadvantages of BC	Suggestions to Treat
	Soil physical conditions		
Texture, porosity	- BC can be used to improve soil quality [21,86]	- Soil type is crucial in positive effect [29–32] - Site-specific application needed [10,60]	- Previous selection and study needed to avoid improper use
Surface area, plant-nutrition	- Adsorption and fixing of elements or leachable materials (e.g., nitrate) [37] - Protects soil biota [33,34]	- Plant nutrition might be limited (e.g., in drought conditions) [38,39]	- Consider the stressed environmental condition (watering, soil inoculation)
Aeration, better oxygenation	- Supports aerobic processes, protects soil biota [2,3]	- Potential of reduced SOM and humus content [42]	- Use soil-dependent treatments, add organic materials
	Soil chemistry		
pH	- Near-neutral conditions, better for the soil life [100]	- Some nutritive elements become less available [36]	- Consider current soil characteristics and act accordingly
SOM, humus, carbon	- Sequesters carbon [4,5] - Mitigates climate change [58,59]	- Indirect effect on soil biota might reduce SOM [63,64]	- Proper use might be required
Toxic materials, heavy metals	- Improved decontamination [16,81,89] - Heavy metal adsorption and fixing [99,100]	- Potential accumulation of toxic compounds [5]	- Inoculation by adapted microbes might improve remediation
	Soil biology		
Survival of soil biota	- Large surfaces can provide niche [65–67] - Drought protection and improved stress tolerance [70,84,88]	- Dependence on microbial physiological groups [98] - Limitation in microbial distribution [12]	- Focus on soil-borne plant pathogens might be helpful
Activity of soil biota	- Enhanced plant nutrition [94,96,97]	- Competition with plants for nutrients [43]	- Proper C:N ratio to avoid penthozan effect - Optimization for specific soil–plant systems

6. Conclusions

The major effects of biochar application on soil physical, chemical, and biological characteristics are summarized in Table 5. Regarding the objective of the present review, we have highlighted the benefits and some drawbacks of biochar application. Most of the literature shows that biochar generally contributes to improvement of physicochemical properties in soils, such as their water balance, clay, organic matter content, pH buffering, and the amounts of macro-, meso-, and several microelements, due to its porous structure, aeration, oxygen content, and relative quantity. The available literature indicates, therefore, a wide range of uses of biochar for the development and enhancement of beneficial soil–

plant–microbial interactions. Improvements in plant nutrition may occur via several direct and indirect effects in soils. We have to mention, however, that intensification of soil biological activity is frequently a drawback of biochar application in some soils that are relatively low in soil organic matter and high in aeration, such as the arenosols. In arid environmental conditions, it is the limited water availability that is able to diminish known beneficial effects and reduce the potential nutrient uptake by crops. Integration of biochar into crop production technologies therefore requires preliminary experiments, particularly in considering the effects of symbiotic beneficial bacteria and fungi. The abundance and activity of microsymbionts such as the nitrogen-fixing *Rhizobium* bacteria and phosphorus-mobilizing mycorrhizal fungi can be dose- and product-dependent; thus, optimization seems to be necessary in order to suit specific soil–plant-environment circumstances. Further studies are suggested to efficiently address these drawbacks in biochar application.

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