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Review

Biochar as a Multi-Action Substance Used to Improve Soil Properties in Horticultural and Agricultural Crops—A Review

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Abstract: With climate change escalating to global proportions over the past decade, along with a growing population, methods are being sought to help the natural and cultivated environment function in an ecologically balanced manner. Over the past few years, there has been a significantly increased interest in research on the use of natural substances for sustainable agriculture and horticulture. One of the most effective solutions to the emerging need is biochar, which has been the subject of environmental research for years due to its potential to increase soil carbon sequestration, reduce greenhouse gas emissions, remediate contaminated soil, and alleviate anthropogenic pressures. There is evidence of improved soil fertility and increased crop yields in agricultural production after biochar application. Our work comprehensively describes the effects of biochar on soil properties, crop productivity, and mitigating environmental stresses, and its remediation potential in heavy metal-contaminated soils. We analyzed a wide range of the literature on the most important properties of biochar for various potential uses. We summarized the results of research work over the past two decades to analyze soil and plant responses to biochar application.

Keywords: biochar; biomass; soil conditioner; plant growth; environment

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1. Introduction

The transformation of the natural environment around us has caused progressive pollution of the environment and anthropogenic emission of greenhouse gases, which in turn has resulted in progressive global warming. In addition to the negative impact on the condition of nature, ecosystems, and the Earth's climate, environmental pollution also directly threatens human health [1,2].

Agricultural and horticultural crops are also severely affected by this problem due to abiotic stressors such as too high or low temperature, drought, mineral deficiency, salinity, and intense radiation [3,4]. Environmental degradation affecting agriculture and horticulture also manifests in soil degradation caused by erosion, deterioration of physical properties, or contamination with plant protection products and heavy metals [5,6].

The use of biochar in agriculture is believed to be one of the most promising technologies for climate change mitigation [7–9]. Biochar research has attracted the attention of dozens of teams worldwide [10], and the pool of literature on its versatile applications is extensive [11,12].

Biochar may positively affect soil health, its nutritional status, and the biological activities of the rhizosphere [13]. It can also be used as an additive to the soil to improve its physical, chemical, and biological properties [14,15]. Many authors have shown that the application of biochar in the soil can (1) directly increase the uptake of nutrients by plants, and thus indirectly enhance yields [16]; (2) improve soil properties [17]; (3) reduce greenhouse gas emission [18]; (4) and immobilize heavy metals and organic pollutants [19] (Figure 1).

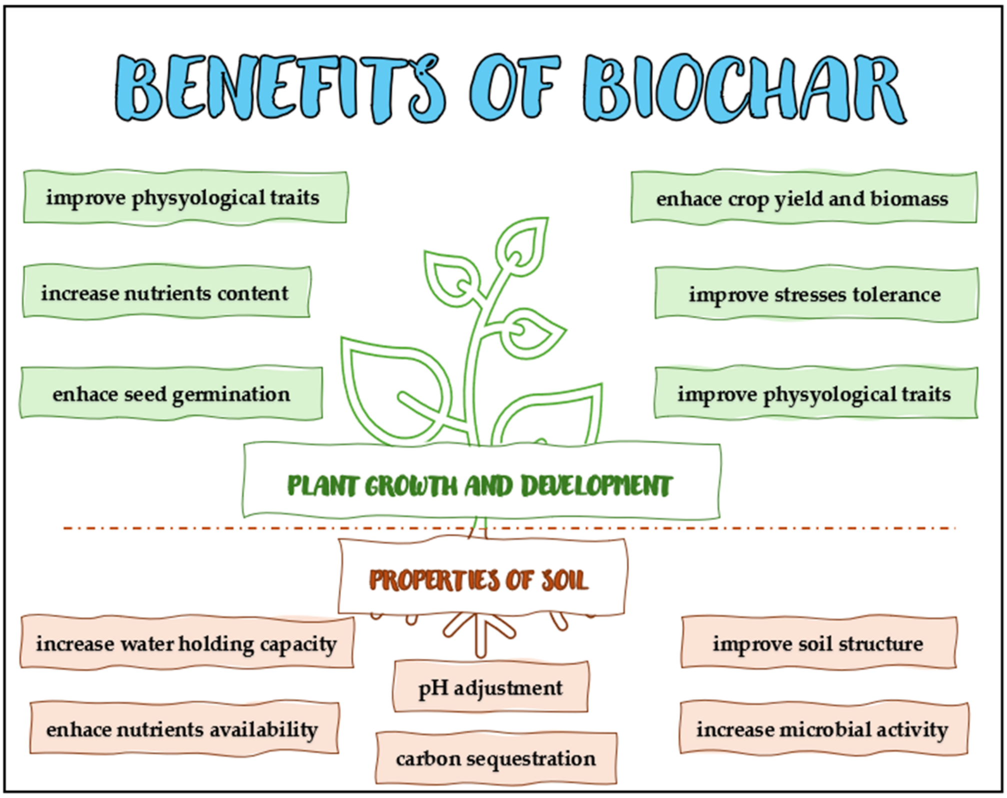

Figure 1. Effect of biochar application on soil properties, plant growth, and development.

The positive effect of biochar on the physiological parameters of plants has also been demonstrated. Indeed, the addition of biochar can significantly increase the rate of photosynthesis, leaf chlorophyll content, and transpiration rate [20,21]. The various advantages of biochar make it a potentially attractive research material for current science and technology [22], especially amid numerous changes in the soil environment.

Among the benefits of using biochar, scientists cite positive agronomic aspects (e.g., maintaining high soil culture and increasing nutrient availability for plants), as well as the ability to mitigate climate change by reducing the negative impact of environmental stresses on cultivated plant species [23–25]. The quality of biochar is mainly influenced by the origin and properties of the substrates as well as the parameters of the pyrolysis process, namely, the temperature, pressure, time, or period of use [26].

This article provides an up-to-date review of current knowledge on the potential uses of biochar as a substance with multifaceted effects both in crop production and its positive impacts on the environment.

2. Literature Review Methodology

2.1. Overview of the Methodology

The literature review in this chapter provides a comprehensive examination of current research surrounding the use of the properties and effects of biochar on soil and plants in horticultural and agricultural crops.

In this article, the literature refers only to biochar obtained in the pyrolysis process.

The methodology employed in this review involves a structured and systematic approach to identify, select, and analyze relevant peer-reviewed articles and academic publications written in English from various disciplines, including agriculture, horticulture, and environmental sciences.

2.2. Search Strategy

A systematic search was conducted across the following academic databases to gather the relevant literature: Google Scholar, Scopus, SpringerLink, PubMed, and Web of Science. The search terms used included combinations of key phrases such as biomass, pyrolysis, gasification, carbonization, soil amendment, soil health, yielding, environmental stresses, remediation, microbial activity, and greenhouse gas emissions. The use of these databases allowed for a thorough study of the issue based not only on the effects of biochar on soil, but also on the environment and crop production. The search was limited to articles published between 2000 and 2024.

2.3. Data Extraction and Analysis of Quality Assessment

Key information about research objectives, methodology, and results related to the impact of biochar on soil, environment, and plant production was extracted from the selected articles. These data were then organized thematically to identify recurring trends in the literature and areas of innovation in the field of biochar use. Each study was critically assessed for its methodological quality, experimental design, statistical analysis, and conclusions drawn.

2.4. Synthesis of Findings

The literature was synthesized into several core themes:

- Effect of biochar on the physical and chemical properties of soils;
- Effect of biochar on soil microbial composition and activity;
- The use of biochar in agricultural and horticultural production;
- The benefits of using biochar for the environment;
- Threats related to the application of biochar to the soil.

The synthesis presents current knowledge about both the positive impact of biochar on soil and plants, as well as the risks resulting from its use.

3. Short Historical Outline of the Use of Biochar

The first references to the use of biochar date back 7000 years, and charcoal, as a precursor to biochar, was known as early as Paleolithic times. Natives living in the area of today's Amazonia transformed the soil through settlement activities. For many generations, it was enriched with charcoal from campfires, burned refuse, animal bones, broken pottery, compost, and manure. As a result, a soil type known as dark Amazonian soil—*Terra preta*—was formed. It is characterized by its dark color, high nutrient content, and ability to retain water [27].

As far back as when the ancient Native American ethnic groups lived in the area, charcoal was used to enrich the soil with nutrients, i.e., potassium, phosphorus, and nitrogen, by combining charcoal with biomass (compost, manure, and agricultural biomass) [28]. Despite the passage of time, these soils are still distinguished by their high productivity and have aroused great interest in the use of biochar in plant cultivation [29]. Throughout Asia, biochar has been used for centuries not only in agriculture, but also in the production of ceramics, ink, and dyes [30].

In the 19th century, its use in agriculture began in Europe and South America. In the 1980s, its use was revisited, and now the properties of biochar are considered more broadly, not only for agricultural purposes but also in waste management and bioenergy [31]. Naturally, biochar finds its way into soils around the world as a result of grassland and forest fires, and lands rich in high levels of biochar are among the most fertile, such as the North American prairies [29].

Nowadays, not only has biochar found applications not only in crop production and environmental studies (to immobilize heavy metals and organic pollutants), but it is widely used in the energy industry and metallurgy, among others [32,33]. Currently, interest in the use of biochar is growing, as evidenced by numerous scientific papers and conferences [34].

4. Biochar—Production and Feedstock Sources

Biochar is a product formed from organic or plant waste subjected to various processes, resulting in a fine-grained porous substance [35], which is known by a uniform chemical composition compared to the starting material [36]. In its composition, it not only contains carbon, but is also rich in ash, hydrogen, oxygen, nitrogen, and sulfur. It can also contain phenols, alcohols, and several aromatic compounds, which ultimately affect its properties [37].

Biochar is mainly produced by the biomass combustion process known as pyrolysis (fast and slow), but there are several methods of obtaining biochar that are constantly being improved to improve the quality of the output product. Based on the literature review that has been carried out, methods such as gasification, torrefaction, hydrothermal carbonization, and electro-modification are used to produce biochar [38], while biocarbon is a solid carbon material that is derived from renewable and sustainable raw materials subjected to thermochemical conversion at high temperatures (>350 °C) in the absence or limited availability of oxygen. It can be used as a component of composite materials and energy storage and conversion [39].

The most popular and cheapest way to obtain biochar is production from the thermal decomposition of biomass, the so-called pyrolysis (slow, intermediate, or fast pyrolysis), carried out under anaerobic conditions at 250–1000 °C (Figure 2). The result is a fine-grained and porous substance with homogeneous chemical composition compared to the starting material [40,41]. Therefore, due to the relatively simple production method and the popularity of its use, this review focuses on biochar obtained as a result of the pyrolysis process.

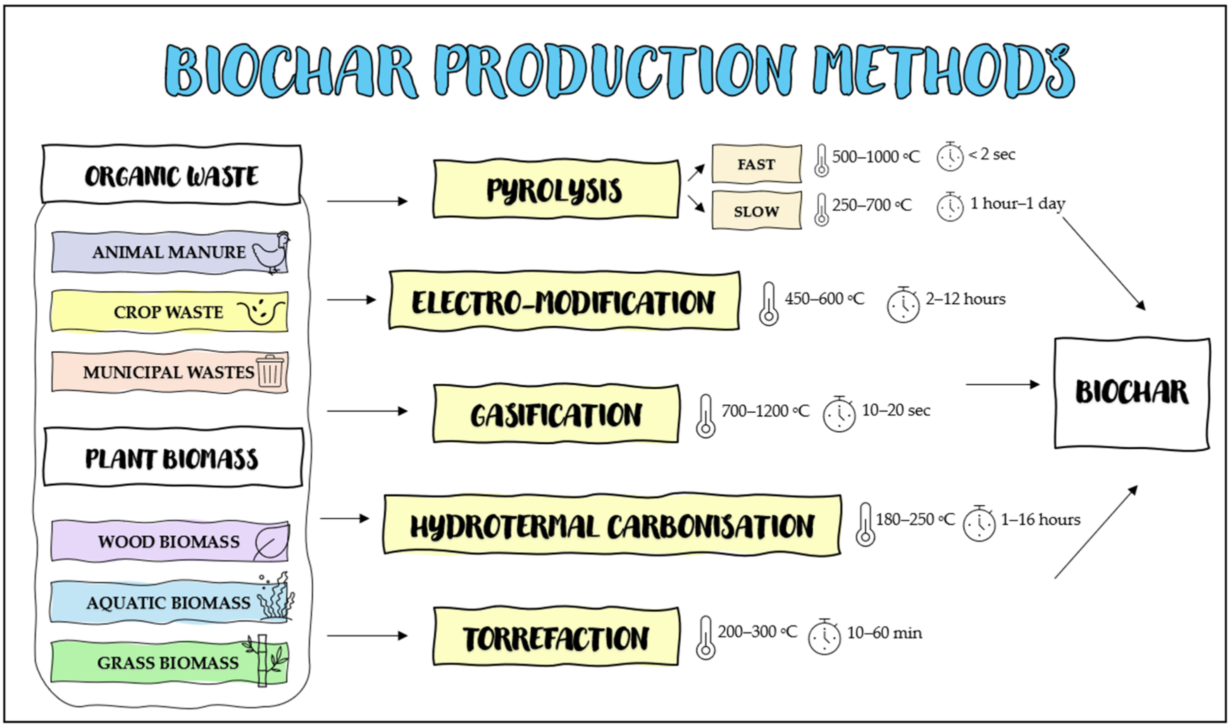

Figure 2. Different methods used for biochar production.

The physicochemical properties and performance of biochar largely depend on the pyrolysis process and the raw material used, which can be agricultural biomass, energy crops (e.g., willow, miscanthus), wood waste (e.g., sawdust, bark), agro-food industry waste, animal manure, sewage sludge, municipal waste, industrial by-products, and aquaculture waste (Table 1) [42–44].

As already mentioned, the physical and chemical properties of biochar (e.g., surface area, pH, or concentration of various elements: carbon, oxygen, nitrogen, phosphorus, potassium, and calcium) depend on the raw materials used and the production temperature [45]. Higher temperatures of the pyrolysis process produce biochar with higher porosity and surface area, a higher C:N ratio, a more alkaline pH, and lower dissolved organic carbon concentrations [46,47].

Temperatures of 350–650 °C rearrange chemical bonds and create new functional groups in biochar (e.g., carboxyl, lactone, lactol, quinine, chromene, anhydride, phenol, ether, pyrone, pyridine, pyridone, and pyrrole). Biochar produced at lower temperatures (300–400 °C) has a more diverse organic character due to the presence of aliphatic compounds and cellulose-type structures. When the pyrolysis temperature increases to 300 °C, biochar contains furans and phenols, but above 300 °C condensed aromatic compounds, aromatic benzenoids and alkylfurans appear. Some authors indicate that biochar produced at temperatures up to 480 °C retains functional groups such as phenolic and carboxylic acid. Biochar produced at high temperatures from 600 to 700 °C is highly hydrophobic in nature, with well-organized carbon layers, but has a lower content of functional groups as a result of dehydration and deoxidation biomass [48–50]. These differences in the properties of biochar are highlighted when it is used as a soil additive [46,47].

Antonangelo et al. [51] report that, as a result of increasing the pyrolysis temperature from 350 to 700 °C, the Cation Exchange Capacity, Specific Surface Area, and microporosity of biochar increased. According to the cited authors, the pyrolysis temperature did not affect the surface functional groups responsible for the retention of heavy metals, which is why biochar pyrolyzed at 700 °C has a much greater buffering capacity and is therefore more promising for improving soil health and reducing pollution bioavailability.

Table 1. Types of biochar according to the raw material used.

Type of Biochar	Pyrolysis Temperature [°C]	Residence Time (Hours)	pH	EC [μS·cm^{-1}]	Product Yield [%]	Ash Content [%]	Elemental Compositions [%]				Cation Exchange Capacity [cmol$_+$·kg^{-1}]	Bulk Density [g·cm^{-3}]	Specific Surface Area [m^2·g^{-1}]	Diameter of Pore [nm]	Total Pore Volume [cm^3·g^{-1}]	Reference
							C	N	P	K						
ORGANIC WASTE																
ANIMAL MANURE																
poultry manure	300	0.3	7.3	8960.0	71.0	n.m.	42.4	5.3	1.26	4.13	69.0	n.m.	n.m.	n.m.	n.m.	[52]
chicken manure	300	0.5	8.1	519.0	n.m.	34.8	n.m.	4.7	0.22	0.51	n.m.	n.m.	n.m.	n.m.	n.m.	[53]
	500	1.0	10.6	662.0	n.m.	38.0	n.m.	1.5	0.14	0.57	n.m.	n.m.	n.m.	n.m.	n.m.	
cow manure	300	n.m.	8.5	n.m.	n.m.	45.0	34.3	2.6	n.m.	n.m.	n.m.	n.m.	3.5	n.m.	n.m.	[54]
	600	n.m.	9.6	n.m.	n.m.	54.5	38.5	2.1	n.m.	n.m.	n.m.	n.m.	13.9	n.m.	n.m.	
swine manure	700	2.0	7.0	n.m.	n.m.	44.0	48.4	2.2	n.m.	n.m.	n.m.	n.m.	319.0	n.m.	0.250	[55]
	400	0.3	10.5	1655.0	70.7	57.6	38.3	1.9	n.m.	n.m.	n.m.	n.m.	7.39	9.5	0.017	[56]
	700	0.5	11.4	1835.0	61.6	71.8	25.0	0.9	n.m.	n.m.	n.m.	n.m.	73.54	3.04	0.056	
CROP WASTE																
husks	400	2.0	8.5	n.m.	43.3	27.0	47.9	1.3	n.m.	n.m.	n.m.	n.m.	39.6	n.m.	n.m.	[57]
	750	n.m.	9.7	900.0	n.m.	48.2	41.0	1.72	n.m.	n.m.	n.m.	0.18	n.m.	n.m.	n.m.	[58]
shells	400–500	2.0	6.4	880.0	n.m.	n.m.	25.3	0.4	0.09	1.39	21.84	0.58	n.m.	n.m.	n.m.	[59]
	400	1.3	10.2	n.m.	39.0	12.2	67.2	3.1	0.41	1.07	n.m.	0.29	2.8	n.m.	n.m.	[60]
	500	1.7	9.8	n.m.	33.0	14.2	69.3	2.8	0.56	1.71	n.m.	0.32	2.9	n.m.	n.m.	
seeds	450	0.7	9.1	n.m.	n.m.	8.2	70.4	3.6	n.m.	n.m.	n.m.	n.m.	3.3	n.m.	0.006	[61]
	550	0.9	9.6	n.m.	n.m.	8.9	73.0	3.7	n.m.	n.m.	n.m.	n.m.	3.8	n.m.	0.007	
	700	1.0	11.3	n.m.	30.0	17.2	82.0	1.3	n.m.	n.m.	n.m.	n.m.	420.3	1.09	0.190	[62]
straws	350	0.3	7.5	1270.0	57.3	11.5	57.5	1.3	0.19	0.10	56.3	n.m.	n.m.	n.m.	n.m.	[63]
	700	2.0	9.5	12,210.0	33.0	40.6	41.0	3.0	n.m.	n.m.	64.8	0.24	n.m.	n.m.	n.m.	[64]
cobs	445	0.9	10.3	2390.0	38.0	10.4	n.m.	n.m.	n.m.	15.40	n.m.	0.15	71.7	n.m.	n.m.	[65]
leaves	300	1.0	5.7	122.0	52.1	5.8	62.5	2.6	n.m	n.m	223.6	n.m.	5.5	n.m.	0.002	[66]
	500	2.0	10.0	n.m.	n.m.	5.2	63.7	4.5	n.m.	n.m.	n.m.	n.m.	17.2	1.42	0.700	[67]
MUNCIPAL WASTE																
sewage sludge	300	11.0	7.2	90.0	43.8	38.2	47.5	n.m.	n.m.	n.m.	44.15	n.m.	n.m.	n.m.	n.m.	[68]
	900	0.5	12.1	n.m.	53.3	88.1	15.9	0.5	2.02	0.87	247.5	n.m.	67.6	3.84	0.099	[69]
solid waste	400	0.5	8.0	n.m.	n.m.	6.1	48.6	1.3	n.m.	n.m.	n.m.	n.m.	20.7	n.m.	0.027	[70]

Table 1. *Cont.*

Type of Biochar	Pyrolysis Temperature [°C]	Residence Time (Hours)	pH	EC [μS·cm^{-1}]	Product Yield [%]	Ash Content [%]	Elemental Compositions [%]				Cation Exchange Capacity [cmol$_+$·kg^{-1}]	Bulk Density [g·cm^{-3}]	Specific Surface Area [m^2·g^{-1}]	Diameter of Pore [nm]	Total Pore Volume [cm^3·g^{-1}]	Reference
							C	N	P	K						
PLANT BIOMASS																
WOOD BIOMASS																
sawdust	500	1.0	7.1	n.m.	19.0	2.4	71.0	0.3	n.m.	n.m.	n.m.	0.43	n.m.	n.m.	n.m.	[71]
chips	500	2.0	6.5	200.0	n.m.	2.6	88.8	0.5	0.03	0.61	n.m.	1.52	6.2	n.m.	n.m.	[72]
stems	450–500	n.m.	9.6	1350.0	n.m.	n.m.	58.5	1.3	n.m.	n.m.	11.0	n.m.	200.5	2.43	0.122	[73]
branches	600	2.2	10.6	n.m.	28.5	9.4	80.0	1.3	0.34	1.14	19.0	n.m.	108.6	1.25	0.058	[74]
GRASS BIOMASS																
alfalfa	650	2.0	8.1	n.m.	27.5	13.6	72.2	4.6	n.m.	n.m.	n.m.	n.m.	405.0	n.m.	n.m.	[75]
cane	400	0.7	5.2	1460.0	21.3	n.m.	46.6	1.0	n.m.	0.55	86.2	n.m.	n.m.	n.m.	n.m.	[76]
	500	0.8	6.2	1630.0	19.5	n.m.	48.8	0.9	n.m.	0.61	44.8	n.m.	n.m.	n.m.	n.m.	
	250	0.4	5.0	n.m.	77.1	n.m.	n.m.	n.m.	n.m.	0.39	n.m.	0.08	0.8	n.m.	0.056	[77]
	600	1.0	7.7	n.m.	22.9	n.m.	n.m.	n.m.	n.m.	3.54	n.m.	0.07	14.1	n.m.	0.141	
miscanthus	450	2.0	9.9	n.m.	30.6	8.2	73.1	0.4	n.m.	n.m.	n.m.	0.28	90.5	n.m.	0.054	[78]
bamboo	500	1.0	n.m.	n.m.	38.0	3.9	82.1	0.5	n.m.	n.m.	n.m.	0.11	n.m.	n.m.	n.m.	[79]
	300	n.m.	6.7	n.m.	73.2	n.m.	66.2	0.4	0.24	0.30	n.m.	n.m.	1.3	n.m.	n.m.	[80]
	450	n.m.	5.2	n.m.	26.3	n.m.	76.9	0.2	0.36	0.35	n.m.	n.m.	18.2	n.m.	n.m.	
	600	n.m.	7.9	n.m.	24.0	n.m.	80.9	0.2	0.50	0.52	n.m.	n.m.	470.4	n.m.	n.m.	
AQUATIC BIOMASS																
algae	350	0.9	9.2	28.0	51.0	33.3	33.9	2.1	0.54	n.m.	44.4	n.m.	1.1	15.4	0.004	[81]
	550	1.3	11.0	32.9	37.9	42.1	33.0	1.9	0.69	n.m.	34.6	n.m.	14.6	5.01	0.018	
	750	2.0	11.2	44.7	33.3	54.2	27.8	1.4	0.67	n.m.	2.3	n.m.	29.8	4.37	0.033	

n.m.—not mentioned.

5. Effect of Biochar on the Physical and Chemical Properties of Soils

Studies have shown that biochar can improve the physicochemical and biological properties of soil, creating a suitable environment for plant roots, enabling nutrient uptake and improving plant growth [82,83].

Among other things, its use affects soil water infiltration, Water Holding Capacity, soil aeration and porosity, bulk density, pH, Cation Exchange Capacity, and nutrient cycling. Biochar has also been shown to remain in agricultural fields for up to several years and, therefore, has the advantage of durability in the environment and soil [84–86]. Table 2 presents examples of the impact of biochar on the physical and chemical properties of soils.

The deep-soil application of biochar contributes to an increase in the organic carbon content and influences its circulation. Thanks to its considerable sorption capacity, it stimulates an increase in the soil's content of micro- and macronutrients [87–89]. Biochar also contains aromatic and aliphatic compounds as well as oxidized carbon compounds, which are extremely valuable for soil microorganisms due to the high content of calcium, magnesium, and carbonates, among others [90–92].

This substance can be used as an additive to compost consisting of organic waste with a high nitrogen content, e. g. manure, chicken manure, or sewage sludge [93]. According to Clough et al. [94], biochar changes the dynamics of nitrogen in the soil. Laird et al. [95] obtained a 7% increase in this element after applying biochar. Many authors also report that adding biochar to the soil has a positive effect on the phosphorus content in the soil. It usually occurs in easily digestible forms, but the ability to change the pH of the soil and the strong dependence of phosphorus on pH is of great importance [96,97].

Adding biochar to soils may change reactions and thus improve plant yield by increasing the availability of nutrients. The pH of biochar is generally alkaline (from 7.1 to 10.5) [48,98] and depends on the type of biomass. It was found that biochar produced from wood has a lower pH compared to other biomass formed under similar pyrolysis conditions (by two units on average) [99].

Specific Surface Area is an important physical parameter that, like many characteristics of biochar, varies based on the raw material from which it was produced (Table 1) [100]. These latter cited authors reported that biochar produced from coconut shell (25.8 $m^2 \cdot g^{-1}$) had a lower Specific Surface Area than biochar produced from sugar cane leaves (253.2 $m^2 \cdot g^{-1}$). Weber and Quicker [101] reported that biochar made from sewage sludge had a surface area of 100 $m^2 \cdot g^{-1}$, while the majority of biomasses possess surface areas ranging from 100 to 800 $m^2 \cdot g^{-1}$. In another study, it was found that biochar from corn straw (*Zea mays* L.) had a larger surface area than biochar from poplar or aspen leaves (*Populus* species) [102].

In soils where biochar has been applied, the agronomic performance has improved. This is due precisely to its Specific Surface Area, and thus its effect on the basic functions of soil fertility, its ability to store water and nutrients, aeration, and microbial activity [103,104].

This substance, due to high Specific Surface Area, also promotes the formation of complex bonds with cations and anions (Cation Exchange Capacity), as well as metals and elements on the soil surface, and consequently improves the soil's ability to retain nutrients [105] (Table 2).

Cation Exchange Capacity is an important element characterizing the quality of soil and its ability to retain positively charged ions, such as calcium, magnesium, and potassium, using electrostatic forces. Cations retained by electrostatic forces are exchanged with cations in the soil solution, thanks to which soil with higher Cation Exchange Capacity has better properties for retaining Ca, Mg, and K, which, however, does not indicate increased fertility, especially in the case where the soil has acid cations in the form of hydrogen and aluminum. The physical, chemical, and biological properties of soil have a significant effect on Cation Exchange Capacity [106].

Water Holding Capacity is the amount of water held by the soil solution against the force of gravity. Water Holding Capacity depends on the soil texture and organic matter content and affects the regulation, drainage, and functioning of the soil. The higher the organic matter content, the higher the Water Holding Capacity. It determines the moisture content required in the soil for plant growth. A suitable soil should be rich in air and water. The physicochemical properties of the soil are of great importance, especially in terms of nutrient and water retention, which affect land productivity [107].

Water Holding Capacity increases water availability for plants, and thus land productivity, contributing to reduced water stress and drought. The physicochemical changes in the soil that occur under its influence contribute to the improvement of its aeration, water infiltration rate, and soil drainage [108].

High porosity promotes the high water absorption, sorption capacity, and nutrient retention of biochar. Hernandez-Mena et al. [77] showed that biochar is characterized by high porosity, where micropores and macropores are distinguished.

Biochar, due to high porosity, also affects the soil's management of air and water [109], significantly improving both the water retention capacity and evaporation resistance [110,111]. Using biochar reduces the bulk density and increases the soil's ability to retain moisture [112]. Since the pore volume of biochar is suitable for effective water retention, it proves to be a promising alternative to peat and vermiculite in horticultural crops [113].

Using biochar as a soil additive may affect the bulk density of soils. Adding about 2% (by weight) may already change the bulk density of soils [114]. Mankasingh et al. [115], after biochar application, showed a decrease in this parameter from 1.66 to 1.53 $g \cdot cm^{-3}$. Also, other studies have obtained changes in this index compared to the control without biochar [116].

Therefore, the reduction in the bulk density of biochar-enriched soil may be one of the indicators of soil structure improvement or aggregation and aeration [117].

It is estimated that the decomposition time of biochar is from 100 to 1000 years. Low susceptibility to degradation and microbiological decomposition contribute to the high stability of biochar in soils [118]. However, some components of biochar may be degraded, and, due to the activity of microorganisms, oxidation, and physical factors, there may be mobility deeper into the soil profile [119,120]. In the studies by Kuzyakov et al. [121], rapid decomposition of the used biochar was obtained in the first three months after its introduction into the soil, followed by a slow and partial decomposition throughout the subsequent years from the start of the experiment.

In the soil profiles of the Amazon River, trace amounts of biochar have been found for hundreds of years. The biochar susceptibility to microbiological processes also depends on soil aggregates [122,123]. Mineralization of biochar occurs to a lesser extent under the influence of abiotic and biotic factors, i.e., climate, type of soil, topography, and the activity of microorganisms [124–126].

Table 2. Effects of biochar on the physicochemical properties of soils.

Type of Biochar	Pyrolysis Temperature [°C]	Dose of Biochar	Type of Soil	Effect on Properties of Soil	Reference
corn residue	350–650	1.0, 2.0, and 4.0 g per 5.0 kg of soil	calcareous sandy loam	increasing soil organic matter content by 1.8 $g \cdot kg^{-1}$, lowering soil bulk density by 0.09 $Mg \cdot m^{-3}$, increasing soil water availability to 0.156 cm^3	[127]
willow wood	350	10.9 $Mg \cdot ha^{-1}$ soil	brown soil	increasing soil pH by 1.2 units, decreasing soil bulk density by 7%, increasing soil total nitrogen content from 4.0 to 6.5 $Mg \cdot ha^{-1}$, increasing phosphorus content in soil from 2.0 to 3.0 $Mg \cdot ha^{-1}$	[128]
oil palm empty fruit bunch	450–500	10.0 $Mg \cdot ha^{-1}$ soil, 20.0 $Mg \cdot ha^{-1}$ soil	sandy soil	increasing soil pH by 2.32 units	[129]
coconut shell	600	10.0 $Mg \cdot ha^{-1}$ soil	acidic soil	increasing soil pH by 1.09 units, increasing soil organic matter by 0.06%, lowering soil bulk density by 0.12 $Mg \cdot m^{-3}$, increasing plant available water by 7.32%	[130]
rice husk	500	380.0 $Mg \cdot ha^{-1}$ soil	clay–loamy soil	increasing soil magnesium content by 64.77% and soil iron content by 25.45%, increasing plant available water from 30.53 to 50.13%	[131]
paddy straw, silver grass residue	500	50.0 $Mg \cdot ha^{-1}$ soil	sandy soil	increasing pH by 0.22 units, increasing soil organic matter content from 37 to 76%, increasing soil calcium content by 3.19%, soil magnesium content by 0.33%, and soil potassium content by 0.87%	[132]
red gram, cotton, maize stalk	350–400	2.5 and 5.0 $Mg \cdot ha^{-1}$ soil	sandy loam	increasing soil pH by 0.6 units, lowering bulk density by 0.05 $g \cdot cm^{-3}$, increasing soil Cation Exchange Capacity from 0.40 to 0.80 $cmol_{+} \cdot kg^{-1}$	[133]
palm kernel shell	400	20.0 $Mg \cdot ha^{-1}$ soil	loamy soil	increasing soil pH by 1.57 units, increasing soil organic matter content by 332.4 $g \cdot kg^{-1}$, increasing soil Cation Exchange Capacity from 0.78 to 0.83 $cmol_{+} \cdot kg^{-1}$	[134]
rice husk	350–400	3.0, 6.0, and 12.0 $Mg \cdot ha^{-1}$ soil	Alfisol	increasing soil pH by 1.21 units, increasing soil organic matter content by 9.41 $g \cdot kg^{-1}$	[135]

6. Effect of Biochar on Soil Microbial Composition and Activity

Biochar is an extremely valuable soil conditioner, as it not only changes numerous soil's physicochemical properties (increases moisture retention and air permeability), but also affects microbial activity [136]. This is confirmed by He et al. [137], who reported that the addition of biochar changes the soil nutrient cycle and supply, which in turn can affect the microbial community (Table 3).

In its structure, biochar has pore spaces, an ideal habitat for microbial and fungal communities [138,139]. Its porous structure promotes the productivity and increased survival of microorganisms in the soil. For example, by comparing biochar from pine bark and biochar from sewage sludge with poultry litter and perlite as a carrier for *Bradyrhizobium* strains, Araujo et al. [140] found that biochar from pine bark was the optimal carrier extending the shelf life of the bacteria to one year. In addition, Hale et al. [141] found that the addition of a mixture of biochar and pine wood bacteria (*Enterobacter cloacae* UW5 strains) to sandy-clay soils increased the bacterial population density by 16%.

The addition of this substance changes the structure of bacterial population in the soil [142]. Bacteria involved in nitrogen fixation (*Rhizobium* sp., *Azospirillum* sp.), nitrification (*Nitrospora* sp., *Nitrobacter* sp.), and methanotrophic bacteria (*Methylobacterium* sp.) showed growth in soil modified with biochar [143].

Soil bacteria are one of the basic factors regulating soil productivity [144]. The presence of soil bacteria promotes nutrient uptake and improves soil aggregation [145]. The addition of biochar can help inhibit or reverse soil degradation processes. Biochar can also promote the growth of mycorrhizal fungi, which contributes to nutrient circulation, uptake, and aggregation in the soil [146,147].

Both biochar and mycorrhiza have the potential to promote soil quality, likely creating synergy between the two elements [148]. Both elements are of increasing interest due to their positive impact on soil fertility, but in the case of biochar, the processes occurring in the soil under its influence are not fully understood.

The interactions of the combination of both components are unspecified and depend on many factors, such as soil structure, organic matter content, and the presence of soil minerals and microorganisms; hence, it is important to continue research to understand the changes taking place [149]. Research on the interaction of biochar with soil microorganisms has been conducted for many years by many researchers, and the resulting reactions to the use of biochar depend largely on the substrate from which it was produced.

Table 3. Effect of biochar on soil microbial composition and activity.

Type of Biochar	Pyrolysis Temperature [°C]	Dose of Biochar	Type of Soil	Effect on Soil Microbial Activity	Reference
eucalyptus wood	not mentioned	1.5, 3.0, and 6.0 $Mg \cdot ha^{-1}$ soil	sandy clay loam	increasing 20–40% of AMF colonization	[150]
Californian pine	not mentioned	15.0 and 30.0 $Mg \cdot ha^{-1}$ soil	silt loam soil	positive influence on promoting an increase effect on bacterial abundance (*Bradyrhizobiaceae*, *Hyphomicrobiaceae*)	[151]
mineral-enriched	450	6.5 $Mg \cdot ha^{-1}$ soil	Red Chromosol soil	promoting the growth of soil microorganism populations by creating suitable habitats for their development	[138]
maize straw	450	2.5, 7.5, and 22.5 $Mg \cdot ha^{-1}$ soil	alluvial soil	biochar application significantly increased the phospholipid fatty acids of AMF	[152]
rice husk	350	3.0, 6.0, and 12.0 $Mg \cdot ha^{-1}$ soil	gray forest soil	alkaline conditions resulting from biochar amendment favor fungal growth over bacterial growth	[153]
amur silvergrass rice straw	500–600	22.2 g per 100 g soil	sandy loam soil	biochar reduced the Pb bioavailability, while rice straw biochar increased the As; biochar addition enhances the dissolved organic matter and AMF growth inside sandy soil	[154]
agricultural wastes	600	0.0025 $Mg \cdot ha^{-1}$ soil	garden soil	increasing the shelf life of *Burkholderia* sp. and *Bacillus* sp.	[155]

7. The Use of Biochar in Agricultural and Horticultural Production

Biochar is considered one of the alternative soil enrichment practices for sustainable agriculture and the environment [7]. It supports sustainable farming practices, which are essential for the future of agriculture. It also improves soil quality and reduces the need for chemical fertilizers and water, promoting more environmentally friendly agriculture [156,157].

Moreover, biochar has been demonstrated to improve plant growth and development, and thus yield (Tables 4–6), under both optimal growing conditions and stressful conditions, such as water deficit and excessive soil salinity (Tables 7 and 8) [158].

In laboratory and field studies, biochar has consistently shown significant beneficial effects on plant growth and development, resulting in increased crop yields and productivity (Table 4) [159,160]. For example, the use of biochar from grass has been shown to increase the yield of onion (*Allium cepa*) [161]. A positive effect of biochar has also been observed by Carpenter and Nair [162], who showed a higher weight of carrots after using this substance.

This substance can provide oxygen for seed germination and increase seedling growth and development by improving soil aeration and reducing soil bulk density (Table 4) [163]. Latini et al. [164] showed an increase in fresh and dry mass in five varieties of durum wheat after the use of biochar resulting from wood chips and wheat straw. Biochar from wheat straw clearly increased the aboveground maize biomass and its root system (including total volume, surface area, and number of maize root tips) [165].

In their research on the impact of biochar on soil properties, Petrova et al. [166] found that biochar can increase soil fertility and retention capacity, which in turn leads to improved plant growth conditions and better yields.

Table 4. Impact of the application of different types of biochar on plant growth, development, and yield.

Type of Biochar	Pyrolysis Temperature [°C]	Dose of Biochar	Type of Soil	Plant Species	Effect on Plant Growth and Development	Reference
rainbow eucalyptus	350	25.5 and 45.5 g per 1.0 kg of soil	inceptisol soil	rice (*Oryza sativa*)	increasing grain yield from 232.0 to 250.0%	[167]
wheat straw	507	15.0, 30.0, 75.0, 150.0, and 225.0 Mg·ha^{-1} soil	loamy sand soil	sunflower (*Helianthus annuus*)	increasing seed germination from 8.0 to 31.0%	[168]
bamboo	500	2.0 and 5.0% per 1.0 kg soil	clay loam soil	cherry tomato (*Solanum lycopersicum*)	improving growth, number of leaves, fresh biomass yield of aboveground and underground parts from 21.0 to 114.0%	[169]
apple branch	450	1.0, 2.0, 4.0, and 6.0% of soil volume	silt–clay soil	durum wheat (*Triticum durum*)	increasing the crop yield by 14.77 to 43.02%	[170]
rice husk	450	50.0 Mg·ha^{-1} soil	fluvo-aquic soil	peanut (*Arachis hypogaea*)	increasing the crop yield by 42.40 and 48.40%	[171]
corn cob	450	20 t·ha^{-1} soil	sandy loam	soy (*Glycine max.* L. Merr)	increasing the rate of seed germination from 24.0 to 27.0%, increasing shoot growth from 22.0 to 27.0%	[172]
walnut shell	550	10.0, 20.0, 40.0, 80.0, and 120.0 Mg·ha^{-1} soil	Petri dish bioassay method	triticale (*Triticosecale* Wittmack), green pea (*Pisum sativum* sp. arvense)	higher germination rate and growth from 69.0 to 97.0%	[173]

Table 4. *Cont.*

Type of Biochar	Pyrolysis Temperature [°C]	Dose of Biochar	Type of Soil	Plant Species	Effect on Plant Growth and Development	Reference
cotton straw	450	1.0 and 3.0% per 15.0 kg of soil	gray desert soil	cotton (*Gossypium hirsutum*)	increasing root dry weight from 7.52 to 13.06 g per plant and shoot dry weight from 95.93 to 136.81 g per plant in harvesting stage	[174]
pinewood	400	5.0, 10.0, 15.0, and 20.0% per 5.7 L pot	Ultisols soil	muscadine grape (*Vitis rotundifolia*)	strengthening the root architecture, increasing the length of roots from 2000.0 to 7000.0 cm and the number of root forks from 3000.0 to 6000.0	[175]

Photosynthesis is a basic and very complex physiological process of plants, determined by many factors, both internal and external. Any reduction in its intensity causes a decrease in the quantity and quality of the crop [176].

Many authors have shown that the use of biochar not only increases the rate of photosynthesis, but also increases the chlorophyll content of leaves, the rate of transpiration, the total content of flavonoids, sugars and glucose, and the Relative Water Content of plants (Figure 3) [177–179]. The beneficial effects of biochar on plants physiological and biochemical traits have been reviewed and are summarized in Table 5.

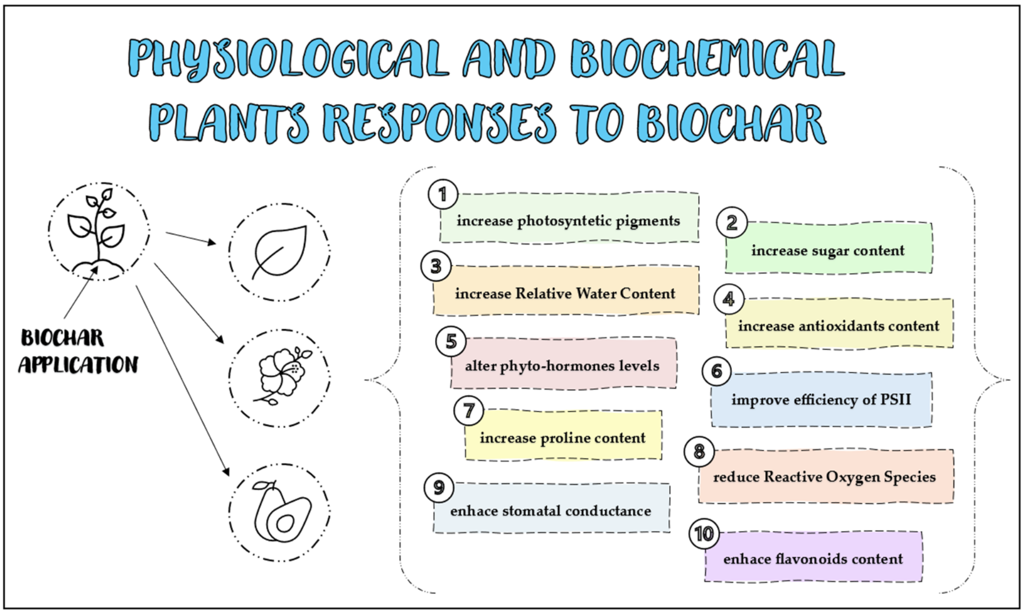

Figure 3. Physiological and biochemical plants responses to biochar.

In studies conducted by Abid et al. [180] and Jabborova et al. [181], the authors noted an increase the total content of chlorophylls and carotenoids in tomato leaves and common basil. Similar results were obtained by Hafez et al. [182], where the addition of biochar stimulated the growth of assimilation dyes in barley. Lévesque et al. [183] demonstrated a 32% increase in the value of the Water Use Efficiency index in photosynthesis due to the use of biochar in tomatoes.

Table 5. Impact of the application of different types of biochar on physiological and biochemical traits of plants.

Type of Biochar	Pyrolysis Temperature [°C]	Dose of Biochar	Type of Soil	Plant Species	Effect on Physiological and Biochemical Traits	Reference
Lantana camara stems	450	10.0 and 30.0 g per 1.0 kg of soil	sandy clay	okra (*Abelmoschus esculentus* Moenc)	increasing net photosynthetic rate and Water Use Efficiency	[184]
cotton stalk	not mentioned	5.0 $Mg \cdot ha^{-1}$ soil	sandy clay loam	cotton (*Gossypium* sp.)	increasing Relative Water Content and chlorophyll stability index, decreasing proline accumulated in leaves	[185]
rice husk	450	1.0, 5.0, and 10.0% per soil	not mentioned	soybean (*Glycine max*)	increasing leaf net photosynthetic rate, chlorophyll index, leaf soluble sugar, and starch contents	[186]
black cherry wood	450	2.0 and 3.0% per 400.0 g of soil	loam soil	basil (*Ocimum basilicum*)	enhancing chlorophyll content, total sugar, flavonoids, and soil enzymes activities	[181]
black cherry wood	450	2.0 and 3.0% per 1.5 kg of soil	not mentioned	ginger (*Zingiber officinale* Rosc.)	increasing Relative Water Content, chlorophyll, and carotenoid content	[187]
olive pomace waste	500	40.0 $Mg \cdot ha^{-1}$ soil	sandy loam	olive (*Olea europaea*)	increasing water potential in leaves, net photosynthetic rate, Water Use Efficiency, and electron transport rate	[188]
rice husk	450	20.0, 30.0, and 50.0 g per 1.0 kg of soil	sandy loam soil	tomato (*Lycopersicon esculentum*)	enhancing stomatal conductance, net photosyntetic rate, transpiration rate, and Water Use Efficiency	[189]

Biochar helps improve crop yields and Nutrient Use Efficiency, which leads to improved soil quality, i.e., improved physicochemical and biological properties [190].

It can increase not only the total content of N, K, and P in the soil, but also all the necessary nutrients for plant growth (Table 6) [139,191–193], which are related to its properties—a large number of oxidized functional groups and porous structure [194].

Table 6. Impact of the application of different types of biochar on nutrient availability.

Type of Biochar	Pyrolysis Temperature [°C]	Dose of Biochar	Type of Soil	Plant Species	Effect on Nutrient Availability	Reference
peanut hull, pine chip	400	11.2 and 22.4 Mg·ha^{-1} soil	loamy sand soil	maize (*Zea mays*)	increasing the availability of N, P, K, Ca, and Mg	[195]
wastewater sludge	550	10.0 Mg·ha^{-1} soil	Chromosol	cherry tomato (*Lycopersicon esculentum*)	increasing nutrient availability (P and N)	[196]
poultry manure	550	10.0 and 20.0 Mg·ha^{-1} soil	tropical acid soil	maize (*Zea mays*)	increasing soil availability of N, P, K, Ca, and Mg	[197]
poultry litter, pinewood	350	40.0 Mg·ha^{-1} soil	Ultisols	winter wheat (*Triticum aestivum*)	increasing uptake of Ca, Mg, Na, P, and K	[198]
peach and vine pruning waste	550	4.0, 10.0, 20.0, 30.0, and 40.0 g per 1 L	heavy alkaline-calcareous soil	kiwifruit (*Actinidia* sp.)	increasing exchangeable Fe in the soil, greater absorption of nutrients by plants	[199]
fruit trees wood waste	450	50.0 Mg·ha^{-1} soil	silty clay loam	tomato (*Lycopersicon esculentum*)	increasing N and P uptake	[200]
bamboo, rice	750–800 (bamboo), 500 (rice)	2.5 and 5% per pot	loamy clay	tea (*Camellia sinensis*)	increasing P, K, and Mg concentrations in plants	[201]
wheat straw	400	12.5 g per 5.0 kg of soil	clay–loam soil	rice (*Oryza sativa*)	increasing N, P, K, and Fe uptake	[202]

Many authors have demonstrated positive effects of biochar on plants growing under conditions of biotic and abiotic stress (Tables 7 and 8), particularly its capacity to increase resistance to adverse environmental stressors and to maintain plant growth [203–206].

Because biochar affects the soil, rhizosphere, pathogens, and plant microbiome, it can assist plants in the rapid regulation of defense-related processes, such as oxidative burst, when encountering abiotic and biotic stress [207].

Biochar is effectively used against a wide range of air- and soil-borne plant pathogens, and the mechanisms by which this substance can protect plants from disease are varied [208,209].

A large number of studies indicate that the addition of biochar can confer induced resistance to pathogenic organisms on plants (Table 7). In a study on the control of Fusarium ear rot in maize, it was found that soil amendment of poultry manure biochar and sawdust biochar through effective management of the resident soil pathogens proved beneficial in inhibiting *Fusarium verticillioides* infection [210]. Also, in studies conducted on tomato (*Solanum lycopersicum*), it was found that after enriching the soil with biochar from greenhouse waste, plant infections by *Botrytis cinerea* pathosystem were reduced by up to 50% [211].

Although various soil pathogens can adversely affect crop growth in the form of diseases, benevolent soil microorganisms can displace the negative effects of harmful bacteria and fungi [212]. The action of biochar results in disease inhibition through the aforementioned induction of systemic resistance in plants, i.e., by increasing the density and activity of beneficial microorganisms such as N_2-fixing bacteria [213], plant growth-promoting rhizobacteria [214], and *Trichoderma* spp. [215].

Table 7. Impact of the application of different types of biochar on plants under biotic stresses.

Type of Biochar	Pyrolysis Temperature [°C]	Dose of Biochar	Type of Soil	Plant Species	Effect on Plants Under Biotic Stresses	Reference
citrus wood	450	1.0 and 3.0 g per 100.0 g potting mixture	coconut fiber (peat)	strawberry (*Fragaria ananassa*)	induction of systemic resistance against *Botrytis cinerea*, *Colletotrichum acutatum*, and *Podosphaera apahanis*	[216]
pinewood	550–600	5.0% per 2.54 L pot	substrate (sphagnum peatmoss, horticultural grade perlite, dolomitic limestone)	red oak (*Quercus rubra*), red maple (*Acer rubrum*)	induction of systemic resistance against *Phytophthora cinnamon* and *Phytophthora cactorum*	[217]
eucalyptus wood, greenhouse waste	350–600	0.5, 1.0, and 3.0% per 100.0 g potting mixture	potting mixture	cucumber (*Cucumis sativus*)	suppressing soil-borne pathogen *Rhizoctonia solani* (belly rot)	[218]
poultry fecal waste, sawdust	485	1.0, 2.0, and 3.0 kg·m^2 soil	not mentioned	maize (*Zea mays*)	suppressing the infection caused by *Fusarium verticillioides* (maize ear rot)	[210]
greenhouse waste	350	1.0 and 3.0% per 0.5 L pot	substrate (peat tuff)	tomato (*Solanum lycopersicum*)	mediating systemic resistance against Fusarium crown rot (*Fusarium oxysporum* f. sp. *radicis lycopersici*)	[219]

Abiotic stresses pose a serious threat to crops and global food security. The intensity of abiotic stresses (drought, heat stress, salinity, and soil acidification) continues to increase, negatively affecting crop productivity [220]. Biochar is a carbon-rich product used as an important soil conditioner to improve soil quality and plant performance [221]. Its effect on plant physiological traits and soil properties contributes to the development of a resistance mechanism in plants to environmental stresses [222]. The beneficial effects of biochar abiotic stresses on plants have been reviewed and are summarized in Table 8.

It has been shown repeatedly that salinity stress adversely affects plant growth and development and yield [223]. It causes weaker seed germination, hinders plant nutrient uptake, and contributes to a decrease in the activity of antioxidant enzymes [224–226].

Biochar application brought favorable changes in soil and plant functioning to improve salinity stress tolerance [221,227]. As reported by Parkash and Singh [228] and Kerbab et al. [229], this substance reduces the toxic effects of salinity by increasing the efficiency of the photosynthetic process, regulating water relations in plant cells, accumulating osmolytes, secondary metabolites, and hormones, increasing antioxidant activity, and thereby reducing the production of reactive oxygen species in plants (Table 8). Abo-Elyousr et al. [230] indicated that the application of biochar improves the anatomical and physiological properties of mung bean plants under salt stress conditions. A range of research authors have revealed that in plants exposed to salt stress, stomatal density and stomatal conductance improved after soil application of biochar [158,231,232].

Drought stress is one of the most serious abiotic stresses, affecting crop yield reduction to a great extent [233,234].

In fact, under water deficit conditions, the stomata close, which contributes to a decrease in CO_2 content and thus photosynthetic efficiency [235]. There is a loss of plant cell turgor as a result of reduced leaf water content [236]. Drought is a factor limiting the growth and development of plants, which affects the course of many physiological and biochemical processes in plants [237]. As a result of the inhibition of gas exchange and thus the assimilation of CO_2, there is a restriction of the synthesis of sugars. The change in the distribution of nutrients causes the need to restrict the energy-intensive processes of growth, and in extreme cases, even generative development. Inhibition of growth, weaker fruit binding and reduction in yield size, and sometimes also deterioration of its quality have been observed during drought in various crop species [238,239].

Biochar, due to its porous structure and thus soil Water Holding Capacity, affects water availability to plants under drought stress (Table 8) [240]. For instance, Langeroodi et al. [241] showed an increase in water content in pumpkin leaves growing under water-scarce conditions in response to biochar application. The positive effect of biochar application was also observed by Trupiano et al. [222], who reported an increase in photosynthetic rate, chlorophyll content, and transpiration rate in plants. Biochar also improves the gas exchange capacity of crop leaves and reduces oxidative stress [177].

Moreover, Gharred et al. [242] and Keabetswe et al. [243] reported that the application of biochar under water-deficient conditions improves the nutritional status of plants, affecting biomass growth and production, antioxidant activity, and osmolyte accumulation. It has also been proven that biochar increases nutrient uptake under drought stress conditions (Table 8). This is confirmed by Poormansour et al. [244], who detected an increase in Ca and Mg uptake by faba bean (*Vicia faba*) at different irrigation levels and different doses of biochar.

Under heat stress conditions, the addition of biochar can improve soil bulk density, organic matter content, as well as soil microbial structure and microbial abundance, thereby affecting the size of the plant root system [245].

Table 8. Impact of the application of different types of biochar on plants under abiotic stresses.

Type of Biochar	**Pyrolysis Temperature [°C]**	**Dose of Biochar**	**Type of Soil**	**Plant Species**	**Effect on Plants Under Abiotic Stresses**	**Reference**
			SALINITY STRESS IN CROPS			
dried leaves, sawdust	350	1.0 and 2.0% per 10.0 kg soil in pot	not mentioned	wheat (*Triticum aestivum*)	improving germination and growth, and root and shoot length, increasing leaf water potential and osmotic potential under salinity conditions	[246]
Conocarpus wood	300	12.0 g per 4.0 kg of soil	not mentioned	tomato (*Lycopersicon esculentum*)	improving plant growth and total yield under salinity stress	[247]
softwood, hardwood	not mentioned	0.625 g per 12.0 kg of soil	sandy–clay–loam soil	eggplant (*Solanum melongena*)	minimizing impacts of salinity stress, enhancing stomatal conductance and photosynthesis rate, decreasing leaf temperature and electrolyte leakage in leaf tissues, better root growth, shoot growth, and fruit yield	[228]
wood	250–300	30.0 and 45.0 g per pot	silty clay loam	maize (*Zea mays*)	improving plant height, number of leaves, leaf area, fresh and dry shoot biomass, and fresh and dry root biomass under salinity conditions	[248]
			DROUGHT STRESS IN CROPS			
wheat straw	450	3.0 and 5.0 g per 100.0 g soil	clay loam with sand, silt, and clay	rice (*Oryza sativa*)	increasing total chlorophyll content in leaves under drought conditions	[249]
woody branches of button mangrove	450	3.0% per 100.0 g soil	seed cradle	chickpea (*Cicer arietinum*)	increasing root and shoot length, Relative Water Content, chlorophyll content, and membrane stability index	[250]
hornbeam wood chips	450–500	10.0, 20.0, and 30.0 $g \cdot kg^{-1}$ soil	clay loam	chestnut-leaved oak (*Quercus castaneifolia* C.A.M.)	alleviating effects of water deficit, improving photosynthesis, stomatal conductance, and leaf nutrient concentration (P, K)	[251]
rosehip seeds	500	0.5, 1.0, and 2.0% per pot	silty clayey loam	sugar beet (*Beta vulgaris*)	improving K, Mg, and Mn content in plants under drought stress	[252]
wheat straw	500	27.88 and 37.18 $g \cdot kg^{-1}$ soil	fine loam soil	wheat (*Triticum aestivum*)	mitigating effects of drought stress, improving the number of fertile tillers, spike length, the number of grains per spike, thousand grain weight, economic yield, and water use efficiency	[253]

Table 8. *Cont.*

Type of Biochar	Pyrolysis Temperature [°C]	Dose of Biochar	Type of Soil	Plant Species	Effect on Plants Under Abiotic Stresses	Reference
rice straw	600	30.0 $Mg \cdot ha^{-1}$ soil	clayey sand	rapeseed (*Brassica napus*)	mitigating the hostile effects of drought stress to reduce malondialdehyde, leaf hydrogen peroxide, and electrolyte leakage by increasing superoxide dismutase, peroxidase, and catalase activities	[254]
TEMPERATURE STRESS IN CROPS						
rapeseed straw	not mentioned	40.0 $g \cdot kg^{-1}$ soil	fluvisols	rice (*Oryza sativa*)	improving protein transport and N assimilation by shoots under heat stress conditions	[245]

8. The Benefits of Using Biochar for the Environment

Biochar has recently received a lot of attention for its potential to slow global warming and improve soil health. It is widely used in horticultural and agricultural production as a soil additive to prevent soil leaching, moisture loss, toxic element accumulation, and fertilizer runoff, among other benefits [255,256].

The substance also finds applications in environmental management, such as in offsetting excess greenhouse gas emissions, carbon sequestration, soil and groundwater remediation, and wastewater treatment (WWT) [257,258].

Contamination of soils with various substances is growing global concern, posing a significant threat to the environment and human health [259]. The increase in the content of heavy metals, polycyclic aromatic hydrocarbons, dioxins, and furans covers an increasing number of affected areas [260]. All these pollutants have a toxic effect on ecosystems by permeating from the soil to plants and soil microorganisms and then to groundwater [261,262]. In response to the existing problems, new, efficient, and at the same time, cheap remediation options are sought, along with the simultaneous revitalization of land and improvement of plant growth [263,264].

The use of biochar to remove heavy metals from soils is a positive and promising strategy, due to its low production costs and exceptional efficiency [265], compared to other heavy metal removal methods, such as chemical precipitation, ion exchange, electrodialysis, or membrane filtration [266]. The presence of functional groups on the surface of biochar gives the potential to adsorb toxic substances such as manganese (Mn) and aluminum (Al) in acidic soils as well as arsenic (As), nickel (Ni), copper (Cu), cadmium (Cd), and lead (Pb) in soils contaminated with heavy metals [267,268]. Table 9 presents reports on the impact of biochar on the remediation of contaminated sites.

Many authors report that adding biochar has a positive effect on cleaning the environment of substances commonly considered toxic, thus limiting their availability to living organisms [269,270]. Modified biochar is considered as a soil treatment agent that can rehabilitate soil contaminated with heavy metals by improving soil properties [271].

Fahmi et al. [272] showed that biochar from empty fruit bunches can help remove lead and cadmium from soils. Also, Gong et al. [273] demonstrated the positive effect of pyrolysis on the stabilization of heavy metals (cadmium, chromium, zinc, lead, and copper) in biomass derived from *Boehmeria nivea* used for phytoremediation. In addition, Koh et al. [274] observed a decrease in the concentration of arsenic and heavy metals in the soil with the addition of biochar, compared to the control variant.

These effects are mainly due to the biochar structure. Indeed, biochar has a large Specific Surface Area, porous structure, and the ability to exchange cations, which makes it an efficient sorbent for various pollutants, both organic and inorganic [275]. This substance has great adsorption capacity due to its permeable structure and asymmetric plates [276,277].

There are also reports indicating the phytostabilizing abilities of plants for the reclamation of heavily contaminated (As and Pb) piles [278]. The latter authors showed that fine particles of biochar allowed *Salix viminalis* to grow on contaminated soil, allowing the species to be used for phytostabilization.

Dai et al. [279] indicated that organic pollutants under the influence of biochar are sorbed twice as fast as in natural organic matter. It has also been reported that during the production of biochar from biomass obtained from areas contaminated with heavy metals, toxic elements volatilized during the pyrolysis process at a higher temperature (700 °C) [280]. Additionally, in soils where biochar formed from contaminated biomass was used, it did not show any adverse effects on microorganisms [281,282]. This reflects a promising effect on the economy, especially in the case of land that requires phytostabilization or is heavily industrialized and exposed to high levels of heavy metals.

Table 9. Effect of biochar in the remediation of contaminated land.

Type of Biochar	Pyrolysis Temperature [°C]	Dose of Biochar	Type of Soil	Effect in the Remediation of Contaminated Land	Reference
oak wood-derived	400	4.0% per 3.5 kg soil	settling pond soil	reducing the phytoavailable contents of Cu, Pb, Ni, and Zn in soil	[283]
rice straw	500	33.0 and 65.0 Mt·ha^{-1} soil	red soil	increasing soil pH and nutrient content, immobilizing Cd	[284]
vegetable wastes	500	5.0 g per 100.0 g soil	sandy loam	achieving Pb immobilization of 87%	[285]
willow	500–700	1.0 g per 50.0 mL soil	soilless	reducing the concentration of Pb, Ni, and Cd in the soil	[286]
rice husk	400–600	0.5, 1.0, and 2.0% per 280.0 g soil	clay loam soil	reducing the bioavailability of Pb from contaminated land	[287]
paulownia	700–800	1.0 g into a 100.0 mL polycarbonate tube	polycarbonate tube	reducing the concentration and minimizing the availability of Cu, Pb, and Cd in the soil	[288]

Heavy metal stress is a serious threat to plants, causing morphological, physiological, and biochemical changes in plants, which most often leads to a reduction in their biomass and yield [289].

As a result of this type of stress, there is an accumulation of reactive oxygen species in plants and cell damage occurs due to the excessive production of free radicals [290]. Heavy metal toxicity interferes with plant metabolism, disrupting the primary process for plant growth and development—photosynthesis [291], as well as indirect processes such as respiration, transpiration, and acquisition of micro- and macronutrients [292,293]. In addition, metal toxicity stunts root growth and reduces root hair formation [294]. Consequently, due to phytotoxicity caused by metal ions, yields and crop quality are also reduced.

The answer to this type of stress may be biochar, which is being studied for environmental remediation, reduction in mobility of contaminants in contaminated soils, and reduction in adverse changes caused by elements such as arsenic, cadmium, chromium, copper, lead, mercury, and nickel in agricultural and horticultural crops [8]. Biochar can capture toxic compounds such as pesticides and herbicides or organic impurities (i.e., agrochemicals, antibiotics, and other hydrocarbons) [295,296], reducing their bioavailability and thus their accumulation in crops such as wheat (*Triticum aestivum*) [297], lettuce (*Lactuca sativa*) [298], and alfalfa (*Medicago sativa*) [299].

Many studies, represented in Table 10, reported that adding biochar to the soil reduced the uptake and toxicity of metals to the plant.

Table 10. Effects of biochar on alleviating heavy metal stress (HMS) in crop production.

Type of Biochar	Pyrolysis Temperature [°C]	Dose of Biochar	Type of Soil	Plant Species	Effect on Alleviating Heavy Metal Stress	Reference
rice straw	500	5.0 and 10.0 g per 100.0 g soil	not mentioned	sedum (*Sedum plumbizincicola)*	reducing the concentration of Cu, Cd, and Pb in soil	[300]
woody biomass	500	1.0, 2.5, 5.0, and 10.0% per 1.0 kg soil	loamy sand	maize (*Zea mays*)	decreasing Pb and Cd toxicity, immobilizing them into more stable forms	[301]

Table 10. *Cont.*

Type of Biochar	Pyrolysis Temperature [°C]	Dose of Biochar	Type of Soil	Plant Species	Effect on Alleviating Heavy Metal Stress	Reference
eucalyptus wood, bamboo, rice husk	550	5.0, 10.0, and 20.0 Mg·ha^{-1} soil	not mentioned	rice (*Oryza sativa*)	alleviating soil Al toxicity	[302]
cotton straw	350–550	46.8 Mg·ha^{-1} soil	not mentioned	cotton (*Gossypium hirsutum*)	reduction in Cd accumulation in plant organs	[303]

Soil acidification is a natural process that occurs globally [304], but intensive agricultural practices such as fertilization and pesticide use can also lower the pH of soils [305]. When the pH value is lowered below 4.5, aluminum, manganese, and iron ions are activated, which, when present in excess in the soil solution, exhibit toxicity to plants [306].

Liming is the standard treatment to raise soil pH and minimize the negative effects of soil acidity on crops grown [307]. Recently, an alternative method in the form of biochar has also emerged as a liming material for controlling soil acidity [308,309].

Biochar has repeatedly been shown to have a positive effect on reducing soil acidity (Table 11), improving the soil pH, increasing exchangeable cations, and decreasing exchangeable aluminum [310,311]. The application of biochar on acidified soils increases the availability of nutrients in the soil and the absorption of nutrients (N, P, K, and Mg) by plants [312].

Evidently, biochar has positive effects on lowering soil acidity, thereby improving plant growth and development (Table 11). Das et al. [313] showed that this substance also accelerates seed germination, increases shoot and root length, weight and shoot biomass in maize, and black gram in acidic soil. Similar results were obtained by Nguyen et al. [314], who demonstrated that biochar added to acidic soil increased elephant grass biomass yield.

Table 11. Effects of biochar on mitigating soil acidification stress in crop production.

Type of Biochar	Pyrolysis Temperature [°C]	Dose of Biochar	Type of Soil	Plant Species	Effect on Mitigating Soil Acidification Stress	Reference
peanut shells	400–800	not mentioned	soilless	cabbage (*Brassica oleracea*)	increasing plant height, biomass production, and root growth, higher soil pH, and reduced Al concentration in the soil	[315]
poultry litter	600–700	15.0 g·kg^{-1} soil	acid soils	maize (*Zea mays*)	higher soil pH, decreasing in exchangeable soil acidity, increasing in the content of bioavailable N, P, K, Ca, and Mg in the soil	[316]
bamboo, rice straw	750–800	2.5 and 5.0% per pot	loamy clay	tea (*Camellia sinensis*)	higher soil pH, increasing concentration of P, K, and Mg in plants, reduction in soil-available Mn and Cu concentrations	[201]
corn stover	500	25.0 Mg·ha^{-1} soil	acidic soil	bean (*Phaseolus vulgaris*)	reducing soil acidity, decreasing bioavailability of Ni	[317]

One of the most important environmental problems of the 21st century is global warming, caused by the rising emissions of greenhouse gases (GHGs), and the carbon cycle plays a key role in both causing and mitigating it [318]. The main long-lived GHGs are, in descending order, atmospheric carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [319]. Therefore, biochar represents huge potential in terms of mitigating climate change, primarily through carbon sequestration and reducing greenhouse gas emissions, as well as reducing waste biomass combustion and producing clean bioenergy [320].

According to Woolf et al. [321], the global use of biochar would offset 12% of current anthropogenic CO_2-C-equivalent greenhouse gas emissions. In addition, Jia et al. [322]

reported that adding biochar to the soil reduces emissions not only of CO_2, but also of other potent greenhouse gases, especially nitrous oxide and methane (Table 12). The reduction in CO_2 emissions is due to the close binding of biochar to soil particles [323]. For example, peanut shell biochar reduced the total CO_2 emissions of soil by 33%, while biochar from wheat straw reduced CO_2 emissions by 90.25% [324].

Moreover, biochar can reduce emissions of both carbon dioxide and nitrous oxide [325]. Zhang et al. [326] showed that long-term biochar (2 or 7 years) reduced N_2O emissions by 48% in acidic soils and by 22% in alkaline soils compared to control soils.

For instance, Rondon et al. [327] observed almost complete inhibition of CH_4 emissions from a grassland (*Brachiaria humidicola*) and soybean crop, with the application of biochar at 20 $g \cdot kg^{-1}$ soil. These authors also reported a decrease in N_2O emissions from the same crops, by 50 and 80%, respectively.

Table 12. Impact of biochar on reducing greenhouse gas emissions.

Type of Biochar	Pyrolysis Temperature [°C]	Dose of Biochar	Type of Soil	Effect on Reducing GHG	Reference
wood shavings	650	12% (by volume) of dairy cattle slurry	sandy loam	77% NH_3 emission reduction, 63% N_2O emission reduction, 84% CO_2 emission reduction	[328]
pinewood	495–505	1.14 and 4.56 $kg \cdot m^{-2}$ soil	dairy cattle slurry	23% NH_3 emission reduction, 30% H_2S emission reduction, 26% indole emission reduction	[329]
pine chips	400	5.0 and 20.0% of mass of poultry litter	poultry litter	NH_3 emission reduction by 58%, H_2S emission reduction by 71%	[330]
poultry litter	550	10.0% of dry mass of poultry manure-wheat straw	mixture (poultry manure wheat straw)	N_2O emission reduction of up to 75%, up to 40% of total N retained in the composting mixture	[331]
willow woodchips	350	5.0 and 10.0% mass of poultry manure–wheat straw	mixture (poultry manure–wheat straw)	44% NH_3 emission reduction	[332]

9. Threats Related of Application Biochar in Crop Production and the Environment

The use of biochar in the cultivation of crops on agricultural soils has excellent potential. Although the literature reports positive effects of biochar on plants, such as improving plant growth and reducing the accumulation of harmful substances in plants, the toxic effects of biochar on plants cannot be ignored (Table 13). Much depends on the composition of the biomass used to produce biochar and the conditions prevailing during the pyrolysis process [333].

Potential disadvantages related to the soil application of biochar include binding and deactivation of agrochemicals, mainly pesticides [334], influence on seed germination [335], processes, and potential release of toxic substances such as heavy metals [336] and PAHs [337,338] that may be present in biochar.

The use of biochar, derived from raw materials containing heavy metals, significantly increased the Cd(II) content in plants, even in minimally contaminated areas [339]. Similar results were obtained by Zhao et al. [340], who found that the addition of pig manure and sewage may release heavy metals—Cu(II) and Zn(II)—into soils.

Using biochar to retain organic and inorganic substances in the soil may contribute to disturbances in the nutrient uptake of plants and thus the quality of the final yield [341,342]. Especially in the case of food, where high quality and compliance with specific standards are required, it has not been clearly stated whether the changes occurring due to biochar affect its quality parameters [343].

Biochar can also have a negative effect on plant growth and development. Huang et al. [344] indeed revealed that the addition of this substance reduces the germination rate and root length of Chinese cabbage (*Brassica juncea* L.).

Additionally, the presence of biochar in the soil can reduce the biomass of microbes evenly distributed across different functional groups. As a result of changes in the soil environment, some phylotypes will become competitive or limit certain groups of microbes, which in turn leads to changes in the composition of the community and the diversity of populations of bacteria and fungi [345,346].

It is extremely difficult to interpret the results confirming the risk of using biochar in crop production, but in the future, the focus should be on studying the toxic effects of biochar at the cellular and molecular level to reveal the underlying mechanisms [347].

It is, therefore, crucial to implement mitigation strategies to address these potential risks and minimize their impact. These strategies should include testing for toxic content in biochar, assessing its quality, and considering the specific feedstock–application combinations and geographical contexts in which it is applied [348].

Furthermore, integrating biochar deployment scenarios with climate models can help quantify its climate interactions and develop simplified metrics for individual studies [349]. Overall, thorough investigation and careful consideration of potential risks are necessary when applying biochar to soil to ensure sustainable and responsible agricultural practices [350].

Table 13. Threats related to the application of biochar in crop production and the environment.

Type of Biochar	Pyrolysis Temperature [°C]	Dose of Biochar	Type of Soil	Threads to Crops and the Environment	Reference
beech wood	550	72.0 $Mg\cdot ha^{-1}$ soil	chernozem, Cambisol	reducing nitrogen absorption of corn by 44%	[351]
greenhouse vegetable waste	500	85.0 $Mg\cdot ha^{-1}$ soil	paddy soil	inhibiting the scale of the soil microbial community	[352]
paper fiber sludge, grain husks	550	20.0 $Mg\cdot ha^{-1}$ soil	Haplic Luvisol	decreasing soil water content, due to increasing soil salt content and blocking pores	[353]
poultry manure	400	15.0, 20.0, 25.0, and 30.0 $Mg\cdot ha^{-1}$ soil	Red Yellow Latosol	increasing soil salinity, amplifying the sodium adsorption ratio and exchangeable sodium percentages	[354]
apple branch	550	1.0, 3.0, 5.0, and 7.0% soil volume	silt loam	increasing total soil erosion	[355]
eggplant shoots	<500	12.0 $Mg\cdot ha^{-1}$ soil	clay loam soil	increasing soil pH and conductivity, which translated into a 6% reduction in potato yield	[356]

10. Conclusions and Future Perspectives

Using biochar in crops as a soil additive is an ideal alternative to other admixtures with high carbon content. There is a noticeable growing interest in this subject, as more and more scientific papers describing the advantages and disadvantages of its use are being published. Currently, the obtained results confirm the efficiency of its use, but it depends mainly on the conditions of pyrolysis, the substrate used, and the properties of the soil. Biochar may modify soil properties; however, due to its poor fertilization values, it is best used as an addition to fertilizers already in use.

The influence of biochar on the soil structure remains a big mystery. Numerous studies have shown soil aggregation, while others have shown no effect. However, its sorption abilities have found application in cleaning soils from residues of plant protection products, heavy metals, and polycyclic aromatic hydrocarbons.

Furthermore, its influence on the colonies of soil microorganisms has not been fully understood. Based on the currently obtained research results, biochar can successfully be an additive to composts because it is an excellent structure-forming material, binds excess water, and increases the activity of microorganisms and retention of nutrients.

The long-term impact of application of biochar in crop production shows a lot of promise in improving soil quality and increasing yields, but the effectiveness of its use in the long term is still a multifaceted problem. When evaluating the effectiveness of application of biochar, it is necessary to consider its stability and aging in the soil due to a number of mechanisms (biological degradation by soil organisms, abiotic oxidation, and changes in temperature and moisture).

To obtain the best and most reliable results in determining the appropriate method of biochar production and use in the future, it is necessary to carefully consider and characterize the climatic and soil conditions of the study area, considering the long period of research, and determine the best physicochemical parameters for the produced biochar. It will allow us to create a certified, high-quality product that is safe and positively impacts the natural environment in the future.

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