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REVIEW

Function of Biochar: Alleviation of Heat Stress in Plants and Improvement of Soil Microbial Communities

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ABSTRACT: Global warming is making plants more susceptible to heat stress. Hence, adjustments to crop production systems are required for global food security. Heat stress (HS) poses a threat to the quality of ecosystems and global food security due to its adverse effects on plant development. The degree to which HS affects physiological disruptions, physical harm, and biochemical changes at various growth stages directly correlates with its effects on physiological functions, plant growth, and crop production. One promising approach is soil modification using biochar, which enhances soil health and promotes the development of microbial communities, ultimately improving plant heat tolerance. Biochar enhances soil structure, improves moisture retention, and increases nutrient availability in hot weather, thereby promoting plant growth and enhancing crop yields. Additionally, biochar, with its porous structure and ability to provide a liming effect, increases the diversity and activity of soil microbes, thereby fostering advantageous symbiotic relationships. These microbial communities support nutrient cycling, root growth, and general soil health, strengthening biochar's position as a long-term solution for climate-resilient farming. Earlier research concentrated on the connection between biochar and heat stress or microbial populations; however, this review uniquely combines all three elements, providing a fresh viewpoint on their interrelated functions in enhancing plant adaptability. Furthermore, this study demonstrates the potential of biochar as a sustainable component for improving soil and supporting crops that adapt to heat stress. It examines the processes underlying these interactions and provides recommendations for future research strategies.

KEYWORDS: Biochar; heat stress; soil health; plant development; agriculture; abiotic stress

1 Introduction

The continuous increase in global temperatures brought on by human activity and other means is one of humanity's main concerns worldwide. When the temperature increases beyond what a plant can withstand, heat stress occurs, which interferes with the plant's physiological functions (such as photosynthesis rate, transpiration rate, and stomatal conductance) and biochemical functions (phenolic content, carotenoid content, chlorophyll a, and chlorophyll b) [1]. This is triggered by prolonged exposure to high ambient temperatures, particularly during critical growth phases such as fruiting and flowering. Furthermore, in agricultural fields, a lack of shade or protective cover increases direct exposure to sunlight, exacerbating heat damage. The greater severity and frequency of heat waves are predicted as evidence of climate change. Therefore, this decreases the growth, survival, and production of plants [2]. A new analysis by the National Aeronautics and Space Administration (NASA) predicts that climate change will impact wheat and corn output as early as 2030, with a 24% decrease in grain yields [3]. Other research estimated that rice grain output declined by 10% with each 1°C increase, while wheat production is expected to fall by 3%–4% for every 1°C increase [4].

Soil microbiology refers to various microorganisms in soil, including bacteria, fungi, archaea, protozoa, and viruses, which interact with plants and the environment. Although these bacteria, fungi, and archaea are essential for maintaining soil structure, cycling nutrients, and promoting plant development, they can also harm plants and ecosystems in some situations. The majority of the biomass in the soil is composed of bacteria (70%–90%), with fungus coming in second [5]. The third type of life, archaea, lives in extreme conditions essential to maintaining ecological balance and soil health. They release nutrients, establish relationships with plants through plant residues, and directly impact plant development. Additionally, they improve soil fertility, create aggregates, and construct soil structures [6]. Fungi and bacteria are crucial for the breakdown of organic matter, the inhibition of pathogen growth, the enhancement of nutrient cycling, and the texture and structure of soil [7]. However, modifying the soil can help lessen the impacts of heat stress.

Biochar is a porous substance that is made by hydrothermally treating raw biomass or by pyrolyzing it [8]. Pyrolysis is the term for the high-temperature thermal depolymerization of biomass without the involvement of oxygen, where the carbon content of biomass transforms into aromatic carbon compounds as well as amorphous and graphitic-type structures [9]. The biological, chemical, and physical characteristics of soil, like cations, pH, nitrogen (N), phosphorus (P), and calcium (Ca), as well as soil water retention and hydraulic conductivity, are improved by the addition of biochar. Additionally, biochar has outstanding potential for enhancing the soil's aggregation, porosity, and structure. Additionally, it encourages beneficial bacteria in the soil to proliferate. These qualities make biochar a potentially beneficial solution for reducing both global warming and food insecurity. Biochar can be utilized to enhance nutrient absorption and water-holding capacity. The porous structure of biochar can improve the storage of water as well as the size and distribution of minerals, acting as soil formers [10]. This indirectly supports high microbial activity and survival in general. The liming action of biochar raises the pH and enhances the soil's capacity to exchange cations. This effect prevents nutrients from leaching by altering their availability. Furthermore, when the pH rises, microbial nitrification increases, resulting in nitrate losses and reduced availability of ammonium, a preferred nitrogen source of plants [11]. This might create adverse circumstances for plants, particularly in calcareous soils, which could reduce output [11]. Biochar is a possible nutritional replenishment agent since its nutrient content changes based on the input material and pyrolysis temperature [12]. The physicochemical characteristics of the soil have changed due to the incorporation of biochar; under heat stress, organic matter has improved, and bulk density has decreased. Furthermore, it was observed that the application of biochar to rice plants increased their surface area, promoted root length, and resulted in a higher dry weight during heat stress due to their lower bulk density of soil compared to the appropriate control [13]. Under stressful circumstances, biochar can help plants thrive by retaining nutrients in contaminated soil, enhancing microbial biomass and soil physicochemical properties, and boosting porosity and surface area, which helps to hold onto soil moisture. These alterations imply that adding biochar improves the uptake of nitrogen and its retention in above-ground tissues while encouraging root architecture, which eventually helps to lessen the detrimental effects of heat stress on plants. It is expected that intense heat waves will occur in the future because of the Earth's rising temperature. Applying biochar to crops might be one way to increase their resistance to the stress of high temperatures.

Applying biochar to control soil biota is gaining popularity. The microbial population in the soil is impacted by biochar through altering nutrient availability, signaling between plants and microbes, or interactions with different microbial communities [14]. This is because the porous interior of biochar can shield it from physical harm caused by soil compaction or changes in the soil fauna's diet. In light of their vulnerability to dehydration, the real surface protection of microorganisms within is, therefore, a crucial consideration in handling biochar [10]. Biochar positively impacts the surface binding of gases, such as CO_2, generated in the soil. These indirect processes affect the makeup of microbial communities and the microbiological activity of soils [15]. Less competition, a more suitable habitat, higher porosity, an abundance of nutrients and organic materials and nutrients, and enhanced ability of the biochar's surface to retain water are all potential causes. By its nature, biochar also adjusts the soil's pH, creating an environment ideal for specific microbial communities. Several studies have been conducted concerning improving agricultural soil microbes and enzymes by optimizing and applying biochar. Thus, knowledge about how biochar mitigates plant heat stress by altering soil biota remains limited and incomplete. Therefore, this review's goals are to go over (i) heat stress's adverse impacts on several plant characteristics; (ii) the role of biochar in mitigating these effects; (iii) the way biochar helps soil microorganisms thrive; (iv) how biochar affects soil microbial activity to tolerate heat stress; and (v) how microbial communities react when biochar is added to polluted soils. To close knowledge gaps and create plants that are more resilient to future warming scenarios, we offer recommendations for future research endeavors based on our current understanding.

2 Sources of Biochar

Biochar production occurs mainly through the pyrolysis process, where biomass breaks down thermally within an atmosphere that limits oxygen availability. Temperature affects biochar's physicochemical characteristics as the process occurs between 300°C to 700°C [16]. The temperature level during pyrolysis determines char stability through the amount of carbon content [17]. However, substances obtained from low-temperature processes exhibit increased volatility. Different reactions happen during pyrolysis, especially dehydration, depolymerization, and isomerization, which modify the molecular structure of biochar and affect its physical properties [18].

The effective utilization of biochar in soil amendments depends on its physicochemical properties, which include a high surface area, together with cation exchange capacity and stability, because these characteristics are essential for environmental application. The porous nature of biochar enhances its water and nutrient retention capabilities, which makes it an effective solution to enhance soil fertility and plant growth [19]. Biochar possesses stable carbon properties, enabling it to store carbon efficiently and slow the pace of climate change. Research indicates that biochar properties can be optimized by selecting suitable feedstocks and adjusting pyrolysis conditions. This leads to meeting specific environmental requirements such as soil remediation and heavy metal adsorption [20]. Some raw materials show superior abilities for toxin removal, which makes them suitable candidates for pollution control systems [21].

Biochar is derived from various organic feedstocks. Different types of organic waste (Fig. 1) can be used for producing biochar. Generally, waste sources can be classified into forestry, agriculture, and municipal and industrial waste. Forestry wastes comprise leaves of trees, barks, logs, and various types of plants resulting from forestry operations, whereas agricultural wastes include wastes from plant cultivation and animal farming. Plant farming wastes include crop residues, such as stalks, husks, leaves, and straw that remain after harvesting rice, wheat, sugarcane, corn, and other crops. They also include leftover feeds like grains, forages, and other materials, and harvest and processing waste, such as vegetable trimmings, fruit peels, damaged produce, and by-products from food processing [22]. Livestock or animal farming wastes include the manure of different animals and birds, litter, and carcasses. Municipal and industrial waste includes trash from industry, businesses, households, sewage treatment plants, building sites, and hospitals [23].

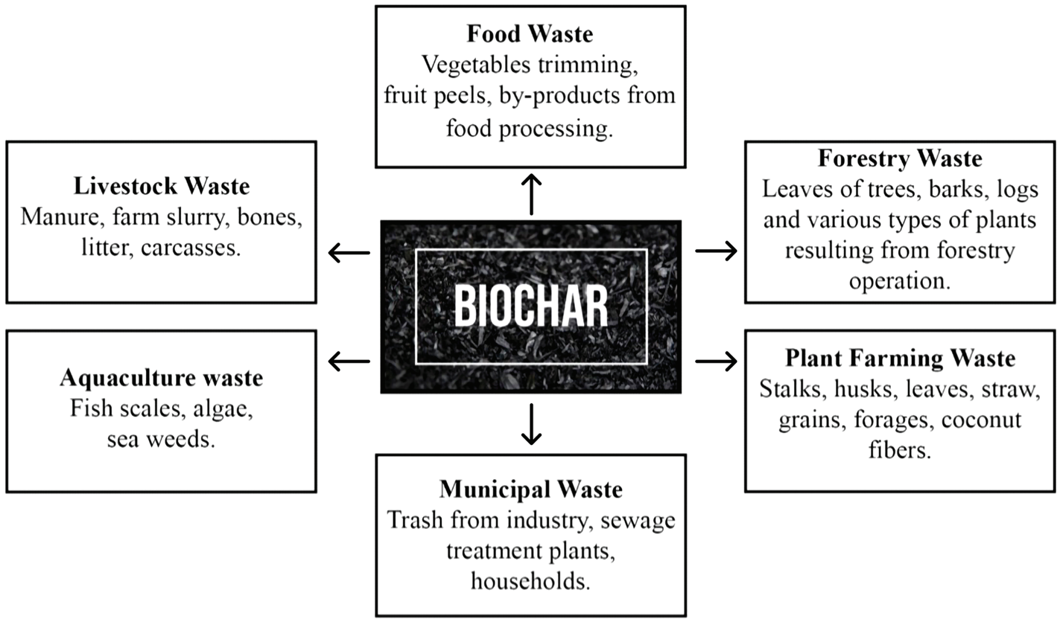

Figure 1: Different waste streams for the production of biochar

3 The Consequences of Heat Stress

Plant growth, development, and reproduction are impacted by the increased frequency, severity, and extended duration of high temperatures brought on by global climate change (Fig. 2) [24]. Heat waves and intermittent spikes in temperature have several detrimental effects on human society as well as the environment, including the potential to affect global agricultural production and future food demand significantly [25]. The rising temperature, when exceeding the threshold border for an extended duration, causes heat stress and impairs the plant's growth and development [26].

3.1 Lowering the Yield of Crops

Although plants can experience heat stress at any stage of development, some growth phases are more susceptible to the effects of heat than others. Particularly in crops, heat stress has significant detrimental effects throughout the thermally sensitive developmental stages of early establishment, blooming, and gametogenesis [27]. Pollen grains are considered the most sensitive plant organ, and anthesis, or the early flowering stage, is deemed the most susceptible developmental stage to heat stress [28]. The final yield of grain is determined by the intricate relationships between several phenophases and their sensitivity to external factors. Reduced fruit set, pollen, seed germination, and yield are some of the negative impacts [29]. Three consecutive days of high temperatures (33°C–40°C) during the anthesis and grain-filling stages of wheat can significantly reduce grain size, weight, and number, resulting in substantial amounts of malformed grains [30]. A single hot day can also severely damage plant organs and reduce grain yield by shortening critical growth stages, such as blooming, anthesis, grain filling, and ripening [31]. Heat stress during reproductive stages leads to significant yield losses. Among the reproductive stages, gametogenesis in common bean [32], and flowering rice [27], sorghum [33], wheat [34], are highly sensitive to heat stress, leading to spikelet sterility and decreased seed and fruit numbers. High temperatures have a direct and detrimental impact on endosperm cellularization during the early stages of seed development, which reduces the sink capacity at the cellular level [29]. Consequently, inadequate seed or fruit filling leads to the sensitivity of storage components' biosynthesis, transportation, or catabolism to high temperatures. For instance, PGD3, a plastidic 6-phosphogluconate dehydrogenase (6PGDH), is required for normal maize endosperm starch generation, and elevated temperatures suppress PGD3's activity [35]. Plants undergo physiological changes as a result of heat stress. Plant development is impeded when the photosynthetic machinery is damaged, which lowers transpiration because of stomatal closure and CO_2 content, inhibits the rates of enzymes like ATP synthases and photosynthetic enzymes, reduces the enhancement of leaves, and speeds up degression [36]. The metabolism of carbon absorption is changed to counteract the impacts of heat stress, remobilizing the starch stored in the chloroplasts of plants and allowing them to withstand the stress phase and also escape additional injury by producing energy, carbohydrates, as well as their derived metabolites [37,38].

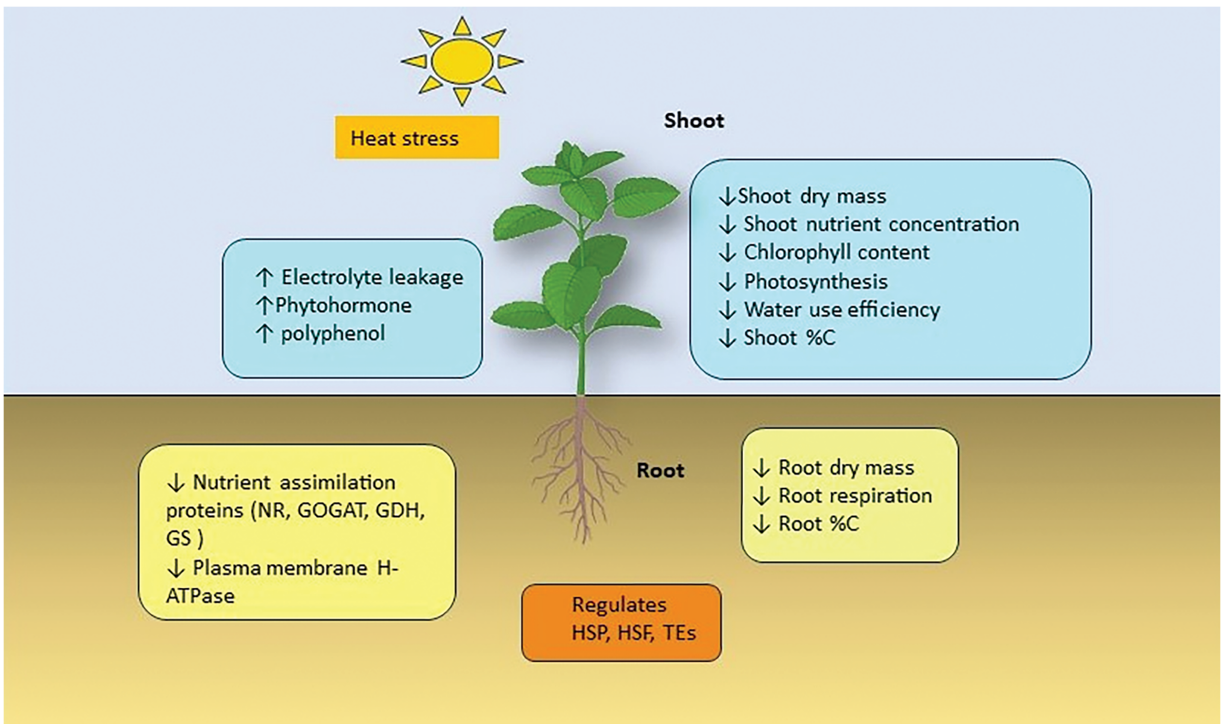

Figure 2: Effects of Heat Stress on Plant Root and Shoot. GDH-glutamate dehydrogenase, GOGAT- glutamine oxoglutarate aminotransferase, GS-glutamine synthetase, HSF-heat shock factors, NR-nitrate reductase, TEs-transposon elements, ↑-increase, ↓-decrease, blue represents an alteration in the shooting process, yellow represents an alteration in the root process, and heat stress-related regulations are represented with orange

3.2 Decrease in the Rate of Photosynthesis

Photosynthesis is the basis of higher plant growth and production. It is an intricate heat-sensitive physiological process. In addition to serving as a metabolic hub for photosynthesis, chloroplasts play a crucial role in detecting heat stress and utilizing retrograde signaling to trigger the necessary physiological adaptation reactions [39]. Heat stress affects several photosynthesis-related activities, such as electron transport, photophosphorylation, calvin cycle metabolism, photochemical reactions, and thylakoid membrane fluidity. Rubisco activase (RCA) is rendered inactive by HS-induced damage to the chloroplast, and key chloroplast components are downregulated [40]. This leads to a reduction in photosynthetic efficiency [41], a redox imbalance [42], and, in extreme situations, cellular death [43]. Due to the rapid and excessive production of reactive oxygen species (ROS), which damage the photosynthetic apparatus by slowing down electron transport, degrading proteins and pigments, and inactivating photosystem II (PSII) and photosystem I (PSI), HS harms plants and ultimately reduces agricultural production [44]. According to Mustafa et al. [42], wheat treated with HS (37°C ± 2°C) during the heading stage had lower levels of carotenoid (48.27%), chlorophyll a (38.05%), chlorophyll b (56.52%), and total chlorophyll (44.12%). According to Wang et al. [40], HS reduced the amounts of chlorophyll in leaves by raising the activity of chlorophyllase and chlorophyll-degrading peroxidase, resulting in chlorosis or leaf senescence. Heat exposure largely impacts the initial stages of photosynthesis, altering the properties of the chloroplasts' membranes and blocking the energy transfer process. Heat stress ranging from mild to severe primarily affects carbon metabolism in the stroma of chloroplasts as well as photochemical reactions in the thylakoid lamellae by damaging photosynthetic enzymes and proteins [40].

3.3 Plant Toxicity

The disturbance of redox equilibrium caused by high temperature leads to oxidative stress, which produces reactive oxygen species (ROS) as well as disrupts the mechanisms that eliminate these toxic forms of oxygen from different cell compartments [45]. The balance of generation and elimination of ROS within cells is disturbed by elevated temperature, leading to the abundance of oxides such as H_2O_2 and malondialdehyde (MDA). This, in turn, exposes plants to oxidative damage when they are facing oxidative stress [46]. Apart from non-enzymatic methods such as ascorbate (ASA), glutathione(GSH), α-tocopherol, and flavonoids), the detoxification of excess ROS generated by stressed cells entails the involvement of ROS-scavenging enzymes like superoxide dismutase (SOD), ascorbate peroxidase (APX), monodehydroascorbate reductase (MDHAR), dehydroascorbate reductase (DHAR), and glutathione reductase (GR) [47]. It was widely believed that the build-up of different ROS, like hydroxyl radicals, superoxide (O_2-), singlet oxygen ($^1O_2$), and hydrogen peroxide (H_2O_2), beyond the antioxidant capacity of plants, was extremely harmful and might significantly impact plant growth. According to reports, excessive accumulation of ROS causes DNA damage, protein oxidation, lipid peroxidation, as well as cell death [48]. The protein function and activity of fruit cells are altered by oxidation driven by ROS, which also accelerates the ripening process [49]. A viable method for producing heat-tolerant crop plants is to manipulate photosynthesis using enzymes involved in the detoxification of ROS and rubisco activase [50].

3.4 Changes in Hormones and Gene Expression

Thermal stress reduces the synthesis of heat shock proteins (HSPs), their transcription and translation, the generation of phytohormones and antioxidants, and modifications to cell structure that affect hormonal equilibrium [51]. For cells of plants to withstand heat stress, temperature rise promotes the biosynthesis routes of hormones like auxins, ABA, brassinosteroids (BRs), cytokinin (CK), ethylene (ET), jasmonate (JA), and salicylic acid (SA). This leads to a higher accumulation in plant cells [51]. Plant gene products fall into three categories. Heat shock proteins (Hsps), ubiquitin ligases, RNA helicases, ion transporters, and aquaporins (AQPs) are among the proteins in the first group that most likely contribute to tolerance for heat stress [52]. RNA helicase, ubiquitin ligases, and HSPs mostly regulate the metabolism of proteins and RNA during heat stress. Heat stress affects the expression of membrane channel proteins, including AQPs and SUTs, which are involved in transporting water, small solutes, and carbohydrates. The second group comprises transcription factors, mitogen-activated protein kinases, calcium-dependent protein kinases (CDPKs), and other regulatory proteins [46]. They significantly impact the control of the transduction of signals, including the gene expression that responds to heat stress. It also modifies membrane fluidity, activating Ca^{2+} channels and causing a Ca^{2+} influx [53]. When plants experience heat stress, signal transduction pathways are activated by Ca^{2+} signals that are transduced by Ca^{2+} sensors to various substrates [46]. Low hormone levels can function as a signal molecule under heat stress, regulating various biochemical as well as physiological responses in vegetation. The internal regulatory lncRNA-miRNA-mRNA network is formed by the interaction of miRNAs and lncRNAs with other substances such as DNA, RNA, and proteins, which increases plant heat tolerance [52].

4 Role of Biochar on Plant Physiology and Development under High Temperature

Biochar is a kind of charcoal made by burning biomass or organic material in a low-oxygen atmosphere. Improving soil, carbon sequestration, and reducing the effects of climate change are just a few uses for biochar. In plant physiology, biochar's enhancement influences root morphology optimization and nitrogen efficiency. Plants can use water and nitrogen (N) more effectively due to this optimized root system, which increases yields [54]. Biochar makes up for yield losses brought on by less N fertilizer application by lowering soil N losses. It supports the partial factor productivity of nitrogen and steady yields of the element [55]. Interestingly, a study team that applied biochar to maize discovered that plant height rose by 4.13%–14.91% across all treatments and that the biomass of the leaves, roots, and steams significantly increased as the amount of biochar applied increased [56]. Researchers discovered that the application of biochar also improved physiological parameters associated with the reduction of drought stress in plants, including electrolyte leakage (–42.5%), peroxidase (–13.14%), water use efficiency (38.41%), transpiration rate (39.17%), stomatal conductance (42.76%), chlorophyll a (19.3%), chlorophyll b (22.24%), photosynthetic rate (24.86%), catalase (24.11%), hydrogen peroxide (–18.03%) and superoxide dismutase (24.66%) [57]. Although not affect the available soil water content, biochar has been demonstrated to enhance the ability of soil to retain water. Applying biochar + P resulted in a 7% increase in the average grain production per plant of rice compared to other temperature treatments and cultivars [58]. Applying biochar and P under extreme temperatures increased antioxidant activity in both Huanghuazhan and IR-64 compared to other treatments. Each antioxidant was tightly controlled in each cultivar leaf and xylem sap. Stress from high temperatures, especially at night, causes plants to grow taller. Putting biochar on the ground, with or without P, improved performance in his experiment [58]. Additionally, rice grain and related traits like the weight of 1000 grains, spike filling rate, rachis dry weight, breadth, and size increased when biochar and P were applied under extreme temperatures [58].

5 Using Biochar to Mitigate Plants' Heat Stress

To facilitate long-term carbon sequestration, the distinctive characteristics of biochar may impact soil bulk density and porosity [59]. Furthermore, it mitigates the adverse impacts of heat stress on rice, maize, and potato crops [13]. The accumulation patterns of heat-shock proteins in plants, induced by heat stress and crucial for developing heat stress resistance, are strongly linked to nitrogen availability. Applying biochar amendments enhances this availability in soil [13]. Riaz et al. [60] have linked biochar to improvements in soil quality, yields, crop growth and development, and soil fertility, as well as a decrease in the number of abiotic stressors. Its large surface area, reactive functional groups, ability to exchange cations, and susceptible carbon are all thought to contribute to these advantages. Heat stress causes plants to lose more water and release less carbon dioxide, which lowers the photosynthetic rate and biomass output. The soil is supplemented with Biochar to boost fertility and maintain long-term production. Controlling daily and seasonal soil temperatures may also influence the thermal dynamics of the soil environment [59]. Regarding boosting soil fertility and production, biochar is important in mitigating plant heat stress (Table 1).

Table 1: Biochar application and its effect on heat stress response in various crops

Type of biochar	Studied crop	Dose	Findings	References
Acacia seyal Biochar	*Sorghum bicolor*	5 t/ha	Increased yield and gas exchange during drought, suggesting better physiological responses to heat stress	[61]
Cork powder fly ash	*Solanum lycopersicum*	Applied with arbuscular mycorrhizal fungi	Enhanced tolerance to combined heat and salinity stress	[62]
Cattle manure	*Arabidopsis thaliana*	10 g kg^{-1} soil	Enriched the expression of the *Zn-finger* gene and *DNAJ* heat shock protein	[63]
Coffee Waste Biochar	*Solanum lycopersicum*	10 t/ha	Improved soil moisture retention, which lessens the effects of heat stress and improves growth performance	[64]
Eucalyptus biochar	*Thymus vulgaris*	5%	Considerably reduced the heat-stressed thymus plants' electrolytic cell leakage	[59]
Horse Manure Biochar	*Hordeum vulgare*	12 t/ha	Increased microbial diversity and nutrient cycling result in increased resistance to heat stress	[65]
Lignocellulosic Biochar	*Glycine max*	10 t/ha	Increased yield and water usage efficiency by mitigating the detrimental impacts of salinity and drought	[66]
Mixed Agri-residual Biochar	*Vicia faba*	9 t/ha	Enhanced enzymatic activity and enhanced nutritional availability to prevent heat stress damage	[67]
Poplar Wood Biochar	*Lactuca sativa*	20 t/ha	Favorable impacts on output and growth under heat stress, indicating enhanced soil qualities and microbial activity	[68]
Rice-husk	*Oryza sativa*	10 t/ha	Enhanced physiological features and root morphology. Decreased expression of heat-shock proteins improves tolerance to heat	[13]
Straw	*Oryza sativa*	40 g kg^{-1} soil	Heat stress mitigation, improvement of root zone environment	[13]

(Continued)

Table 1 (continued)

Type of biochar	Studied crop	Dose	Findings	References
Sawdust Biochar	*Brassica juncea*	10 t/ha	Discovered to greatly reduce the impacts of heat stress while increasing the amount of organic matter in the soil	[69]

5.1 Reducing Emissions of Greenhouse Gases

Carbon dioxide, nitrous oxide, and methane are the main gases that contribute to atmospheric radiative forcing. Other sources include wetlands, animals, fertilizers, agricultural practices, and human activities. The amount of greenhouse gases (GHGs) released by biochar-supplemented soil depends on several variables, including biomass types, temperature, pyrolysis conditions, and soil type [70]. The soil's ability to function as a source of $\mathbf{N_2O}$ is reduced by adding more biochar because it increases the microbial immobilization of readily available nitrogen. Adding biochar, for example, by increasing the microbial immobilization of the readily available N in the soil, reduces the soil's capacity to function as a $\mathbf{N_2O}$ source [71]. It was found that burning paddy straw released 2.09% of its N as $\mathbf{N_2O}$ and resulted in the emission of 0.66, 7, and 70 percent of C as $\mathbf{CH_4}$, CO, and $\mathbf{CO_2}$, respectively [72]. In addition to its ability to sequester carbon, biochar has the ecological benefit of reducing the release of greenhouse gases in soils (Table 2).

Table 2: Impact of biochar application on greenhouse gas emissions reduction

Feedstock used for biochar	Rate of application (%)	Greenhouse gas emission reduction (% compared to control)			References
		CH_4	N_2O	CO_2	
Bamboo	2–10 dw	12.5–72.9	12.4–81.6	5.5–72.6	[73]
Cornstalk	10 fw	15.5	–	–	[74]
Chicken manure	2–10 dw	20.5–61.5	4.7–15.1	–	[49]
Green waste	10 dw	77.8–83.3	68.2–74.9	–	[75]
Hardwood + Softwood (4:1)	27.4 dw	77.9–83.6	16.1–35.3	21.5–22.9	[76]
Holm oak	10 dw	95.1	14.2	52.9	[77]
Tobacco stalk	10 dw	41.7	64.9	26.1	[40]

Note: fw = fresh weight, dw = dry weight.

5.1.1 Nitrous Oxide (N_2O) Emission

Through the use of biochar, the emission of nitrogen dioxide during the process of composting is minimized by fixing the NH_4^+ and NO_3^- ions and thus diminishing the proportion of the inorganic nitrogen utilized by the nitrifying and denitrifying microorganisms [78]. The outer layer of the biochar can actively accept and lessen N_2O by either biotic or abiotic processes [79]. The enzymes involved in N_2O formation and reduction during denitrification are the ones encoded by *nirK/nirS* and *nosZ* genes [80]. The biochar surface can absorb and reduce N_2O through biological or abiotic reactions. The enzymes responsible for N_2O production and consumption during denitrification are encoded by the *nirK/nirS* and *nosZ* genes [80].

Studies conducted in the field and incubation have shown that soils treated with biochar may reduce $\mathbf{N_2O}$ emissions. For example, in a field experiment, paddy soil was treated with biochar made from heated wheat straw (*Triticum sativum*) to 350°C–550°C. According to the findings, $\mathbf{N_2O}$ emissions dropped by 50% and 70% at application rates of 10 and 40 Mg ha^{-1}, respectively, but $\mathbf{CH_4}$ emissions rose by 31% and 49% [81]. Nevertheless, $\mathbf{N_2O}$ emission from amended sandy loam was suppressed up to 98% in another investigation that used hardwood biochar; this effect was independent of the biochar amendment's enhancement of soil aeration [82].

5.1.2 Carbon Dioxide (CO_2) Emission

Recently, a study showed that composting biochar derived from pig dung significantly reduces CO_2 emissions. Conversely, several studies have shown conflicting findings. For instance, it was discovered a surge of 53.2% was discovered in the trend [83], whereas in another study it was discovered a decline of 26.1% [40]. These differences could be attributed to the fact that biochar enhances external organic matter, accumulates, or provides the microorganisms a better habitat, thus enhancing their activity in capturing carbon [84]. Despite these implications, the reduced availability of O_2 sources used by anaerobic bacteria in compost heaps may reduce outputs of CH_4 and N_2O [78].

According to Luo et al. [85], adding biochar significantly impacts several soil properties, such as pH, porosity, plant productivity, carbon and nitrogen dynamics, water content, and cation exchange capacity. Each of these elements can significantly influence soil $\mathbf{CO_2}$ emissions. Scientific studies have demonstrated that there might be substantial, negligible, or nonexistent influence on carbon dioxide emissions. For example, adding sugar maple biochar to a temperate forest soil enhanced its $\mathbf{CO_2}$ emissions somewhat, whereas adding 10% biochar to Douglas fir forest soil boosted $\mathbf{CO_2}$ fluxes dramatically [86]. On the other side, the application of biochar drastically reduced $\mathbf{CO_2}$ emissions from pine forest soils by 31.5% [87]. The four processes that underlie the mechanisms underlying biochar application's effects on soil $\mathbf{CO_2}$emissions are as follows: Biochar application has a large adsorption capacity; the labile organic carbon in biochar adds to the soil's variable organic carbon pool; biochar application influences soil physical and chemical properties, which have an indirect impact on $\mathbf{CO_2}$ emissions [88].

5.1.3 Methane (CH_4) Emission

Brassard et al. [89] found that biochar can decrease $\mathbf{CH_4}$ emissions from rice areas that are damp by promoting soil microbial activity linked to $\mathbf{CH_4}$ oxidation and absorption, as well as enhancing soil porosity and lowering bulk density. This decrease in $\mathbf{CH_4}$ production is due to the aerobic metabolic process of $\mathbf{CH_4}$ oxidation, which depends on the supply of oxygen is also a finding from Brassard et al. [89]. According to the research of Hawthorne et al. [87], biochar treatment considerably reduced the amount of $\mathbf{CH_4}$ absorbed by the soil and also boosted net $\mathbf{CH_4}$ oxidation. However, some studies show that adding biochar either decreases soil $\mathbf{CH_4}$ absorption or has no effect on soil $\mathbf{CH_4}$ emissions [90]. For example, in Thailand, the addition of biochar to soil during rice farming resulted in a considerable reduction in cumulative $\mathbf{CH_4}$ emissions, with a fall of 21.1% in the first season and 24.9% in the second [91]. Conversely, in agricultural environments, co-applying biochar and nitrogen fertilizers to soil did not significantly alter $\mathbf{CH_4}$ fluxes [92].

5.2 Enhancing the Conditions of the Soil

Biochar improves soil aggregation by adhering to organo-mineral complexes and mycorrhizal fungi and increasing microbial activity [93]. Adding biochar to soil improves its pH, organic matter, porosity, moisture retention, surface area, and electrical conductivity. High temperatures can cause sand soils to fracture [94]. In this case, biochar helps address the microbial aggregation, proliferation, structure, and porosity of wildfire-impacted soils [95]. To prevent wildfires from spreading and to produce biochar that is useful for land reclamation associated with wildfires, dried vegetation like pine needles and leaf litter pine needles can be used to create biomass charcoal [48]. An increase in temperature causes soils to absorb more energy than they expel, which may change the thermal characteristics of the soil, such as reflectance, temperature, diffusivity, and thermal conductivity [96]. The addition of biochar may enhance the thermal characteristics of soils by managing the distribution of heat among soil particles, surface-energy partitioning, and the accumulation or movement of water and heat in the soil; all of this impacts the soil microclimate [97]. Additionally, biochar amendment enhances plant growth by increasing arylsulfatase, acid phosphatase, and urease, which are crucial for the utilization of sulfur phosphates and nitrogen [98]. However, because high-dose amendments contain resistant aromatic compounds, they may inhibit the growth of fungi. Phenolic compounds, metal oxides, and silica promote the formation of exopolysaccharide biofilms by bacteria [99]. Biochar can promote fungal biomass growth by increasing laccase and manganese peroxidase activities (Table 3).

Table 3: Enhancement of soil conditions through the application of different kinds of biochar

Applied biochar	Dose of applied biochar	Enhancement of soil condition	References
Acacia spp. Biochar	50 + 50 Mg ha^{-1}	Higher pH and soil water-holding capacity	[100]
Biochar made with poultry manure	5% (w/w)	Mitigation of hazardous chromium (VI) in soil	[101]
Corn straw Biochar modified with iron-zinc oxide combination	3% (w/w)	Elevated dissolved organic carbon (DOC), pH, and CEC, as well as the bacterial community, including Chao1, Shannon and Simpson, and lowered DTPA-Cd	[102]
Composite modified Biochar	1% (w/w)	Soil-soluble K^+, Ca^{2+}, and Mg^{2+} increased, while soil-soluble Na^+ and the Na^+ adsorption ratio dropped	[103]
Coconut Shell Biochar	5% (w/w)	Elevated levels of urease, acid phosphatase, dehydrogenase, bacteria, fungus, and actinomyces, as well as soil pH and CEC; invertase was unaffected	[104]
Iron-modified Biochar	3% (w/w)	While total organic carbon increased, the soil's pH, available Fe, available As, available Cd, available Pb, S-CAT, and UE decreased	[105]
MgO-Biochar	4.5 Mg ha^{-1}	Enhanced P availability	[106]

(Continued)

Table 3 (continued)

Applied biochar	Dose of applied biochar	Enhancement of soil condition	References
Particle size modified Biochar	1% (w/w)	While soil-soluble Na^+ and the Na^+ adsorption ratio dropped, soil-soluble K^+, Ca^{2+}, and Mg^{2+} increased	[103]
Rhamnolipid-modified Biochar	2 wt%	Dehydrogenase activity, bacterial and fungal diversity indices, and CO_2 and CH_4 emissions all increased, whereas N_2O emissions decreased	[107]
Rice husk, oil palm, and cacao shell Biochar	30 Mg ha^{-1}	Raised the pH of acidic soil from 4.73 to 5, and raised the soil's CEC	[108]
Sheep manure Biochar	5% (w/w)	Mitigation of hazardous chromium (VI) in soil	[101]
S-modified rice husk Biochar	5% (w/w)	Total Hg concentrations in leachate dropped while rising Leachate complete elimination of mercury	[109]
Wheat Biochar	4 Mg ha^{-1} + 5 g KNO_3	Enhanced P, K, and total N availability	[110]

5.3 Strengthening the Soil's Water Holding Capacity (WHC)

By improving the soil's ability to store water, biochar additions may increase agricultural productivity in dryland areas without irrigation and lower the need for irrigation water. In sandy loam soils, for example, biochar derived from mango wood enhanced water retention by 11%, but in medium sandy soils, it increased it by 137% [111]. Pine biochar application increases soil water retention and plant available water, improving soil water relations for agricultural land use [112]. In silty loam soils, biochar derived from forest waste increased plant-accessible water by 226%, whereas in other soil types, it dropped by 10% [113]. At other matric potentials, there were no impacts seen, although soil water retention and stress-free available water declined linearly with a biochar application rate. Despite these results, applying biochar to plants exposed to high temperatures improves water retention and water consumption efficiency [114]. Yu et al. [115] reported that the research found that raising the retort temperature from 250°C to 750°C increased water holding capacity from 7% to 16%, with an additional 11% increase. The findings indicate that the potential of biochar to increase the amount of water that can be held may significantly impact areas prone to drying up. These findings also suggest that using biochar benefits increasing crop output and soil health.

5.4 Increasing the Organic Matter (OM) Composition of Soil

Applying biochar to arable soils is an important source of stable organic matter (OM) that might replace conventional organic fertilizers. As biochar is high in OM, it can help increase the amount of OM in soil, improving stability, filtration rate, soil structure, nutrient availability, and water-holding capacity [116]. These enhancements increase the reservoir's capacity to store nitrogen, phosphate, and sulfur while reducing its susceptibility to erosion [117]. Compared to wood-produced biochar, biochar formed from manure has a lesser surface area [118]. Elevated temperatures result in a decrease in oxygen and hydrogen levels, as well as an increase in carbon content [119]. Numerous biological and chemical processes in soil are impacted by dissolved organic matter (DOM), a highly mobile and active organic matter component. The amount and composition of DOM directly impact microbial activity, pollutant behavior, and the global C-cycle [120].

Furthermore, research has shown that biochar has the potential to both release native DOM into the soil and simultaneously absorb intrinsic DOM [121]. Despite this, research shows that biochar may either have no impact on soil DOM levels at all or significantly decrease DOM leaching by 20% via the adsorption of DOM species in the soil that are similar to humic and have a high molecular weight [122]. The impact of biochar on soil DOM is a complicated matter that depends on many variables, such as soil characteristics, the features of the biochar, as well as the experiment design. Therefore, understanding how biochar releases and adsorbs DOM in soil is crucial to understanding its impact on soil DOM [120].

5.5 Increasing Bulk Density of Soil

The addition of biochar significantly reduced the bulk density of sandy soil after ninety-one (91) days of incubation, likely due to more water in the control columns. As bulk densities drop, plant roots may get denser and longer [123]. This result has to be confirmed in fields with intact soil structure, crops, and residues since several factors interact to alter bulk density, soil water penetration, and drainage [123]. Prober et al. [124] reported that the addition of low bulk density biochar material led to a considerable drop in soil bulk density after two years in mesic forests treated with 20 t ha^{-1} of green waste biochar. Furthermore, adding biochar was shown to reduce the bulk density of the soil. This is probably because biochar has a low bulk density. A mean decrease in bulk density of 12% was seen following biochar application in 19 out of 22 soils, with reductions ranging from 3 to 31% [125]. Research was conducted by Toková et al. [126] to observe the influence of biochar without nitrogen fertilizer on bulk density where results revealed that greater biochar doses resulted to a gradual decrease in BD, but a considerable drop was seen when treated routinely at 20 t ha^{-1}.

5.6 Heavy Metal Detoxification

Heavy metals in plants contribute to physiological difficulties that change the metabolism and linkages between plants and nutrients, decreasing production and quality of crops [127]. But researchers have demonstrated that, as a consequence of burning biomass at temperatures higher than 300°C, biochar may retain organic contaminants and heavy metals. Additionally, with co-precipitation, ion exchange, metal ion surface complexation, and physical adsorption, it may be mixed with soil as a remediation and amendment agent to reduce the toxicity and bioavailability of heavy metals in contaminated soils [128]. Silver (Ag), arsenic (As), mercury (Hg), cobalt (Co), nickel (Ni), chromium (Cr), chromium (Cr), lead (Pb), cadmium (Cd) are some of the heavy metals that are considered harmful [129]. Besides, stress conditions due to the presence of Pb, Cd, and As inhibit the formation of secondary metabolites, root elongation, leaf chlorosis, and seed germination [127]. In this case, biochar with higher basal pH (>10), a pyrolysis temperature (between 401°C–600°C), and nano sized particle (<2 mm) appeared to help reduce the absorption of Pb and Cd in plants [130]. When applied to sandy soil, biochar increased soil pH by 4.5 units, reduced bulk density by 3%–31%, and increased soil porosity from 42.5% to 56% when applied to maize straw charcoal at 10–60 t hm^{-2} [131]. Consequently, the bioavailability of heavy metals was considerably reduced by these modified soil conditions [130]. According to Tan et al. [132], adding functional groups like OH and COOH to biochar enhances the heavy metals' ability to bind to complexes, which enhances adsorption. Additionally, the minerals in biochar fix heavy metals, producing precipitates that are insoluble and decrease the metals' mobility and availability in soil. Pb precipitated in biochar due to inorganic P decreased its availability and mobility also [133]. To combat this situation, using biochar significantly enhanced proline accumulation, antioxidant activity, and membrane protection against heavy metals [134]. The use of biochar significantly increased the proline accumulation, enhancing antioxidant activities and protecting the plants from oxidative stress [134]. Also, the application of biochar promoted plant development in heavy metal-contaminated soils by improving photosynthetic efficiency, soil properties, antioxidant activities, nutrient absorption, and lowering the availability of heavy metals [135].

6 Biochar as a Microorganism Growth Stimulator of Soil

Changes to the physicochemical conditions of soil can have a beneficial or adverse effect on the microbial population's activity and structure through habitat modification. Soil microorganisms are directly and primarily promoted to flourish by these alterations in soil characteristics. The content and concentration of accessible nutrients in biochar are determined by the production parameters, including temperature and retention period, as well as the feedstock. Raising the production temperature often results in higher biochar pH, C:N, and C:O ratios, total surface area, while decreasing the concentrations of carbon and organic substances dissolved [136]. By supplying labile C substrates for breakdown, biochar benefits microbial populations. Enhancements to the properties of the soil, like a rise in pH, the availability of nutrients like, C, N, magnesium (Mg), potassium (K), calcium (Ca), phosphorus (P), and, the soil's water-retention capacity may encourage soil microbiological growth [137].

Biochar provides excellent habitats for soil biota owing to its higher surface area and porosity. Hence, biochar can control the quantity and functions of specific microorganisms that may benefit from the physical characteristics of biochar. Another significant characteristic of biochar that affects soil microbial development is surface area. Thus, higher surface area and porosity provide additional openings for microbial colonization, based on the temperature during pyrolyzing and feedstock type. The specific surface area and enhanced porosity of biochar are linked to a greater capability to hold water in a variety of soil types, giving microorganisms better water retention actions and expansion [138].

The chemical properties of the soil, particularly pH, which is an important component affecting soil microbial population and behavior, may be dramatically changed when an enough quantity of biochar is incorporated into the soil. Adding biochar generated from maize straw reduced N leaching and raised the soil's electrical conductivity (EC); consequently, alterations were seen in the composition of the bacterial community [139]. A silt loam soil's total P, total N, and organic C levels were raised by applying 30 t ha^{-1} of biochar composed of maize straw, increasing the soil's nutrient availability [140]. Consequently, observations revealed that the AMF/saprotrophic fungus ratio and relative abundances of AMF were greater than those of the control [140]. N-cycling bacterial community structure and abundance in the soil are impacted by soil type and biochar rates [141]. Some effects of applying biochar on the soil's microbial community are illustrated in Table 4.

Table 4: Microbial responses in the soil while applying different kinds of biochar

Feedstock of biochar	Dose (%)	Production temperature (°C)	Soil microbial response(s)	Soil type	Involved possible mechanism(s)	References
Branches of China fir	1 and 3%	550	Increased the abundance of Gram-positive bacteria and Actinomycetes.	Acidic red loam soil	Total PLFA concentration substantially increased in the 3% biochar treatment, which probably indicates the adaptation of microorganisms.	[137]

(Continued)

Table 4 (continued)

Feedstock of biochar	Dose (%)	Production temperature (°C)	Soil microbial response(s)	Soil type	Involved possible mechanism(s)	References
Biochar fertilizer	20 kg/plant		In rhizosphere, the population of *Mycobacterium*, *Crossiella*, *Geminibasidium*, and *Fusarium* were significantly increased, while *Acidothermus*, *Bryobacter*, *Acidibacter*, *Cladophialophora*, *Mycena*, and *Rickenella* were significantly decreased by biochar soil.		Biochar greatly influenced the metabolomics distribution and the pH, organic matter, alkali hydrolyzable nitrogen, AP, AK, exchangeable calcium, and exchangeable magnesium of rhizosphere soils.	[142]
Compost	2%	NA	Several bands in the DGGE profile showed a significant rise in the BC-modified treatment.	A blend of river sediment and compost	Microorganisms may more easily employ the refractory materials in the treated sample because BC offers better space and excellent electronic transmission.	[143]
Fruit tree residues	0, 10, and 20 t/hm^2	550	The dominant phyla (Proteobacteria, Cyanobacteria, and Actinobacteria) were abundant in biochar treated soil.	Clay soil	Biochar changed the physicochemical properties of soil SMC, SP, AN, NN, AP, AK, and OMC, which fosters the microbial community structure.	[144]
Maize straw	0, 0.7, 2.2, 3.7	400	The application of BC affected AMF and the AMF/saprotrophic fungal ratio.	Silt loam	The composition of the soil microbiological community is determined by $KMnO_4$-oxidizable C ($KMnO_4$–C) and soil organic carbon.	[140]
Peanut shell	1%, 3%		Biochar (1% and 3%) increased Gram-negative bacteria and fungal populations.	Silty loam soil	Biochar amendment increased glucosidase, gluconidase, and phosphomonoesterase activity.	[145]
Rice straw and corn straw	20 t/ha		Increased soil bacteria and fungi abundance and altered community structure.	Albic soil	The impacts of biochar on the soil bacteria and fungi community were indirectly driven by alternation of soil nutrient characteristics.	[146]

(Continued)

Table 4 (continued)

Feedstock of biochar	Dose (%)	Production temperature (°C)	Soil microbial response(s)	Soil type	Involved possible mechanism(s)	References
Raw rice husk	2	500	According to 16S rRNA sequencing research, the application of biochar negatively impacted the behaviour of native microorganisms and decreased the quantity and diversity of bacteria.	River sediment	The addition of BC alters the sediment's physicochemical characteristics, negatively impacting the sediment microorganisms.	[147]
Rice straw (RS)	2%, 1.5%	RS400(400°C), RS700(700°C)	Higher abundance of heterotrophic especially *Proteobacteria* and *Acidobacteria*.	Sandy loam soil	Decreased soil pH and increased dissolved organic carbon and NH_4^+-N concentrations with the RS amendment are driving forces that lead to an enhanced soil microbial activity.	[148]
Rice straw and canola stalk		RB350 (350°C) and RB550 (550°C)	Increased the relative abundances of bacterial genera *Actinospica*, *Ellin6067*, Streptomyces and *Massilia*, while decreasing the abundance of Pseudomonas, and Methylobacterium and Nitrosospira.	Highly acidic Ultisol	The addition of biochar significantly increased total porosity, total pore volume and average pore diameter. The pores in soils had positive effects on the microbial diversity and abundance.	[149]
Rice straw (RB), Pig manure (PB), Sludge (SB)	1%	RB 450°C, SB 650°C, PB 450°C	PB and SB enhanced beneficial bacterial phylum *Actinobacteriota* and genus *Nocardioides*. RB significantly enhanced the beneficial fungal genus *Chaetomium*. Three of them combinedly reduced the abundance of the harmful fungal phylum *Basidiomycota*.		Significantly reduce water loss, enhance water retention, increase the soil nutrient content, improve the pH value, regulate microbial communities, increase beneficial microorganisms, and reduce harmful microorganisms.	[150]

(Continued)

Table 4 (continued)

Feedstock of biochar	Dose (%)	Production temperature (°C)	Soil microbial response(s)	Soil type	Involved possible mechanism(s)	References
Sawdust	5.2	550	PLFA biomass generally decreased with increased redox potential and *vice versa*.	Sandy loam	High adsorption affinity of BC for DOC and SOM results in low accessible C Reproduction of N content in addressed soils. Elevated soil pH greater accessible C and OM content.	[151]
Wood biochar	2%, 4%	500	Biochar amendment improved karst soil nutrient conditions and induced microbial community structural shifts.	Karst soil	There was strong relationship between microbial community.	[152]
Wheat straw	13.5 t ha^{-1} $year^{-1}$	350	Biochar reduced the population of total bacteria, fungi, actinomycetes, and gram-positive, gram-negative bacteria, and total phospholipid fatty acids.	Bulk density (1.56 g cm^{-3})	The Changes in soil organic matter and fatty acid were the main reasons to influence the soil bacterial composition community. The fungal community was governed by MBC, MBN, and LAP activities.	[153]

Note: SMC = soil moisture content, SP = soil porosity, AN = ammonium nitrogen, NN = nitrate nitrogen, AP = available phosphorus, AK = available potassium, OMC = organic matter content, PLFA = phospholipid fatty acids, MBC = microbial biomass carbon, MBN = microbial biomass nitrogen, LAP = leucine aminopeptidase, AMF = Arbuscular mycorrhizal fungi.

7 Impact of Biochar on the Structure and Activity of the Soil Microbial Community

7.1 Architecture of Soil Microbial Populations

The enhancement of both chemical and physical properties (density, macroaggregates strength, pH), as well as the water-air soil regime, are mostly responsible for the beneficial effects of biochar that make it suitable for use as an ameliorant in agricultural practices [125]. The rhizosphere's microbial community as well as the plant roots are both directly impacted by each of these effects [84,154].

Phospholipid-derived fatty acid (PLFA), was utilized to evaluate the communities of microbes in an acid soil treated with biochar following 431 days of incubation. The outcomes demonstrated that the treated soil's PLFA levels were greater than those of the control soil [155]. Furthermore, the PLFA showed that biochar Carbon, which is formed at 350°C rather than 700°C, was utilized as a substrate by gram-positive bacteria. Therefore, the research concluded that the biochar's pyrolyzed temperature has a major influence in managing the composition of the soil microbial community, irrespective of the soil's pH [155]. However, when the utilization rate of maize biochar increased, there was a corresponding drop in the relative abundances of bacteria and fungus, as well as the PLFA levels [156]. Biochar's alkalinity, which tends to lower soil microbial community formulation and temporarily suppress activity, is a possible explanation for it.

DGGE (Denaturing Gradient Gel Electrophoresis), qPCR (quantitative Polymerase Chain Reaction) assay, and clone library analysis were used in conjunction with the terminal restriction fragment length polymorphism (T-RFLP) method to identify the 16S and 18S rRNA genes, which were then used to evaluate the structure and abundance of the fungal and bacterial communities in paddy biochar treated soil [157]. The study's findings demonstrated that while bacterial 16S rRNA gene copy counts increased, fungus 18S rRNA gene copy counts decreased upon the addition of biochar. Applying biochar at greater rates (40 t ha^{-1}) reduced numerous bands associated with the *Ascomycota* and *Glomeromycota*, according to the fungal 18S rRNA gene's DGGE bands. Findings from the research show that although the fungi's ability to metabolize the very stable organic C in biochar is limited, the bacterial population's variety may have increased due to the improved soil pH and fertility [157]. PCR amplification, DNA extraction, and DNA sequencing of 16S rRNA gene fragments were used to figure out alterations in the variety of bacteria and community composition in biochar treated soil [139]. The findings of the investigation demonstrated that the variety of bacteria grew along with the utilization rate of biochar. The aforementioned findings from numerous investigations have shown that based on the soil conditions, type of biochar, and time, biochar could change the microbial community's composition to varying degrees.

7.2 Activities of Soil Enzymes

Soil enzymatic activity is directly affected by a range of biochar impacts on soil microbial population, soil properties, and soil activity. One potential method to watch an enzyme-biochar interaction is to look for the process by which the substrates or enzymes adhere to the biochar [158]. Additions of biochar can repair degraded soil quality by enhancing the biological properties of the soil, like elevating activity of enzyme. Due of its capacity for interacting with the roots of plants and stimulate particular microorganism groups, the enzymatic activity of soil is indirectly impacted by biochar. It has been shown that soils treated with different varieties of biochar and under varied soil conditions have higher dehydrogenase activity [159]. The biochar treatment of a fuvo-aquic soil boosted many extracellular enzymes' activity linked to the cycling of soil carbon and sulfur (S), like β-D-cellobiosidase, β-glucosidase, α-glucosidase, sulfatase, and β-xylosidase [156]. Nevertheless, this effect appeared erratic and dependent on the pace at which biochar was added. For instance, the enzyme activity in the soil increased when a minimal 0.5% of maize biochar was applied. Still, it dropped as the biochar was added at concentrations higher than 1.0% [156]. It can be tough to prove a clear causal relationship between soil enzyme activity and biochars because of the soil environment's various kinds of soil, soil enzyme types, and biochar types (Table 5).

Table 5: Enzyme activity in response to various types of biochar

Biochar's types	Soil type	Decreased activity of enzymes	Increased activity of enzymes	References
Corn straw	Acidic loess	Phosphatase, sucrase (high dosage)	Phosphatase, sucrase	[160]
Eucalyptus residue	Sugarcane soil	Acid phosphatase (high dosage)	Aryl sulfate esterase, β-Glucosidase, Urease (low dosage)	[98]

(Continued)

Table 5 (continued)

Biochar's types	Soil type	Decreased activity of enzymes	Increased activity of enzymes	References
Pine	Fort Collins loam	Glucosidase, phosphatase	β1,4-N-acetylglucosamine glycosidase, α-1,4-Glucosidase, Hydrolase	[161]
Peanut shells, Wooden shells, Rice straw, Corn straw	Laterite	Sucrase, urease	Urease, sucrase, cellulase and protease	[162]
Palm shell	Tropical acidic soil	Lignin hydrolase (not signifcantly afected)	Cellulase	[163]
Parthenium plants and WeedsLantana	Contaminated soils	NA	Dehydrogenase, β-glucosidase, Urease, and alkaline phosphatase	[164]
Rice straw	Slurried soil	Acid phosphatase, β-NAcetylaminoglucosidase	NA	[165]
Suaeda salsa *Phragmites australis*	Coastal wetlands	NA	catalase	[166]
Sophora bark Wutong sawdust	Black loam soil	Urease (wutong sawn wood and locust bark)	Sucrase (wutong sawn wood > Sophora bark)	[165]
Wheat stalk Corn straw Rice straw	Reclaimed soil in mining areas	Alkaline phosphatase, β-N-acetylglucosamine enzyme	β-1,4-Glucosidase	[165]

7.3 Reaction of Soil Microbes in Polluted Soils

Biochar added to the soil can reduce the levels of various pollutants that are present. Biochar is widely recognized for its capacity to immobilize pollutants, both inorganic and organic in soils through various processes, comprising precipitation, absorption, co-precipitation, ion exchange, and complexation. In soils polluted with heavy metals, the roles and composition of the microbial population of soil may be indirectly impacted by biochar because the constitution of microbial community can be altered, and soil microbial development can be inhibited or prevented by heavy metal toxicity [167].

Field research was conducted in contaminated soil to investigate the impact of biochar on soil microbial activity and heavy metal availability using Cd, Pb, and Cu. Relative to the control, the quantity of soil bacteria was grown 2.8 times by applying 3.0 t ha^{-1} of biochar produced from bagasse of sugarcane [168]. Microorganisms' activity, population size, and variety are all impacted by heavy metals (Pb and Cd) in soil. By adding biochar, pH of soil is changed and the bioavailability of heavy metals decreased. Compared to the control, it led to a 39% and 930% rise in the populations of actinomycetes and fungi, respectively [169].

The use of biochar improved the microbial composition of the soil and reduced metal toxicity, as seen by a rising level of phospholipid derived fatty acid (PLFA) and decreased metal toxicity in the soil. Studies on dehydrogenase activity and fatty acid methyl ester (FAME) showed that applying biochar made from vegetable waste at 200°C enhanced the condition of heavy metal contained soils by boosting the soil microbial population and related microbial functions [170].

In Cu-contaminated soil, biochar generated from chicken manure lowered Cu bioavailability and boosted microbial activity because Cu is stored in metal-tolerant soil microbial structures [171]. Soil contaminated with lead and arsenic in low-temperature biochar can elevate the variety of actinobacteria, fungus, and both Gram-positive and Gram-negative bacteria [172]. Therefore, in polluted soils treated with biochar, microbial activity is significantly impacted by biochar's capacity to change the organic matter concentration, pH, and accessible nutrients [173]. It is essential to determine how soil microorganisms in polluted soils react to biochar amendments; this reaction is summarized in Table 6.

Table 6: Application of biochar and its effects on the structure and microbiological community of polluted soil

Soil type	Biochar feedstock	Dose (%)	Production temperature (°C)	Soil microbial response	Soil contaminant (s)	Involved possible mechanism (s)	References
Anthrosol	Wheat straw	0.7–2.9	450	fungi population: +370–930% Actinomycetes population: +19–38%	Pb and Cd	Reduced bioavailability of HMs	[169]
Sandy loam	Vegetable waste pine cone	0, 5	200	enhanced biogeochemical reactions and microbial community richness	As and Pb	HMs immobilized in the soil	[174]
–	*Gliricidia sepium* wood	1-5	NA	Elevated C content of soil microbiomass	Heavy metal	lowered the bioavailable HM level. Under HM stress, plant growth-promoting microorganisms boosted plant growth	[175]
–	Poultry, cow, and sheep manures	5	450	In favor of lowering Cr(VI) to Cr(III)	Heavy metal	Cr(III) was the replacement of Cr(VI)	[101]
Sedimentary alfsol	Chicken manure	5–10	500	Elevated dehydrogenase and microbial activity	Cu	Decreased the bioavailability of Cu and accelerated plant growth	[171]
Sandy loam	Sugarcane bagasse	0.1–0.2	450	Fungal population: −62% Actinomycetes population: +280%	Cd, Cu, and Pb	Diminished bioavailability of HMs	[168]
–	*Gliricidia sepium* wood	1–5	900	elevated numbers of bacteria and fungi	Cr	Decreased Cr's phytotoxicity, mobility, and bioavailability in tomato plants	[176]
–	Date palm waste	0.5–3	300	Soil organic carbon, high concentrations of soil microbial biomass C, and soil respiration	Heavy metal	HMs immobilised in the soil	[177]

(Continued)

Table 6 (continued)

Soil type	Biochar feedstock	Dose (%)	Production temperature (°C)	Soil microbial response	Soil contaminant (s)	Involved possible mechanism (s)	References
–	*Gliricidia sepium* wood	1–5	300 and 700	Co-inoculating Biochar with fungi and soil enzymatic activity was increased overall by bacteria	Serpentine soils	Decreased toxicity of heavy metal and encouraged plant development	[158]
Sandy loam	Cocopeat, palm kernel shell, and wood bark	0, 5	500	No appreciable change in the microbial community's quantity and activity	Heavy metal	HMs immobilised in the soil	[178]

8 Potential Damage to the Soil Ecosystem Due to Biochar Application

Biochar benefits soil ecosystems; however, it also poses risks associated with its use. Biochar is created through the use of totally or partially anoxic biomass pyrolysis. The most common materials used to make biochar are urban sludge, livestock manure, or crop straw. With the application of biochar, pollutants contained in these materials can seep into the soil medium, thereby endangering the soil's environment [179].

Furthermore, the proportion of heavy metals in the raw material determines the quantity of heavy metals in biochar. It has been discovered that the temperature during pyrolysis affects the amounts of Cd, Zn, and Pb in biochar [180]. Therefore, it is essential to determine the optimal temperature range for pyrolysis before its application. Consequently, biochar's volatile organic compounds can damage microorganisms when applied to soil. When producing biochar, pyrolysis temperature may impact the presence of the volatile organic component. Typically, the temperature range for pyrolysis is between 300°C to 600°C. These molecules should volatilize as the temperature rises, and certain semi-volatilized organic compounds may accumulate in the biochar [181]. Because the endogenous source of biochar contains volatile organic compounds (VOCs) that hinder the growth of *Bacillus mucilaginosus*, this bacterium was found in lower quantities in the soil after biochar was added [182].

The incomplete combustion of biomass produces a category of organic pollutants known as polycyclic aromatic hydrocarbons (PAHs), which are poisonous and harmful. However, under the right pyrolysis circumstances, the quantity of PAHs in the biochar formed would be reduced [183]. As biochar may absorb PAHs, the impact of PAHs on soil microorganisms is often minimal. This is because the most quantity of PAHs that might be present in the soil environment is significantly higher than the effective PAHs concentration in biochar. This explains why soil microorganisms are not greatly harmed by endogenous pollutants in biochar [184]. The pyrolysis of biochar produces additional contaminants, such as volatile organic compounds and peroxide-amino hydrocarbons, as well as novel environmental persistent free radical pollutants. Specific oxygen-containing radicals known as Environmentally Persistent Free Radicals (EPFRs) are produced when biochar is pyrolyzed. These radicals include peroxy radicals, semi-quinone, alkoxy, and hydroxyl, and they transfer electrons to the biochar's transition metals, like Fe, Ni, and Cu. In systems composed of organic matter and particulate matter, EPFRs maintain a more stable state, producing several EPFRs [185]. Plant roots are harmed by EPFRs, which also induce oxidative stress in plants and prevent seed germination. Furthermore, EPFRs trigger oxidative reactions that harm microbial populations and create oxidative stress in soil microorganisms [185]. Soil microorganisms may be harmed by the EPFRs found in biochar, causing changes in their population dynamics and activity levels. This could hinder plant germination in its early stages [186]. A list of heavy metals, organic pollutants, and other harmful substances with their hazardous effects, which may be present in biochar, are mentioned in Table 7.

Table 7: The detrimental impacts of endogenous biochar pollutants on soil microbes

Hazardous effects	Contaminants	Examples	Reference
Mutagenic effects on microbes, microbial activity suppression, and microbial community structure modification	Organic contaminants	Volatile organic compounds, polycyclic aromatic hydrocarbons	[187]
Modifies the bacterial populations' diversity and abundance and suppresses the action of some enzymes	Other pollutants	Perfluoro octane sulphonate, perfluorinated compound, pentadecafluorooctanoic acid	[188]
Decreases biomass, impedes microbial growth, and modifies microbial enzyme activity	Heavy metals	Pb, Zn, Cd	[185]
Generates oxidative stress, decreases cellular enzyme function, and modifies the structure of microorganisms	Environmentally persistent free radicals (EPFRs)	Hydroxy, alkoxy	[186]

9 Implication of This Study

The application of biochar in farming presents various advantages that strengthen plant resistance to heat stress alongside supporting essential soil microorganisms. This research generates significant value for sustainable agriculture, especially under dual conditions of climate change and soil degradation.

The physical together with chemical properties of biochar enable it to behave as a protective mechanism that allows plants to withstand heat stress. The porous structure of biochar enhances oxygen circulation while boosting the speed of water uptake, resulting in a powerful defense system against heat stress. Scientific studies prove biochar increases soil moisture levels that enable plants to handle temperature variations [189]. Stomatal conductance and photosynthetic efficiency in plants improve during stressful conditions when biochar supplements are used [190]. Additionally, biochar application leads to improved plant development and stress tolerance, as it enhances the availability of water and nutrients for plants [191]. Furthermore, when biochar integrates with soil, it generates dual effects on plant functioning that foster beneficial microbial communities, thereby maintaining soil quality through nutrient processing. Biochar introduction has proven effective in raising microbial diversity while boosting microbial activity, which strengthens both soil fertility and structure [192].

Moreover, biochar enables beneficial microorganisms to flourish while assisting them in metabolically active behavior that improves soil performance as a plant growing environment [193]. Biochar combined with soil microbial communities can enhance plant growth nutrient supplies, especially nitrogen, through this relationship [194]. Soil resilience against abiotic stresses such as heat and salinity receives added strength through this collaborative effect on plant health [195]. Additionally, the implementation of biochar delivers long-term benefits to soil quality, establishing it as a lasting and sustainable approach to enhancing agricultural production. Biochar enhances soil structure by increasing cation exchange capacity and water retention properties, thereby contributing to improved crop yields [196]. Agricultural development depends heavily on these enhancements because climate change produces progressively severe and frequent weather events. Biochar implementation enhances soil health and plant resistance, offering agricultural operators a compact method to reduce climate change effects [197].

10 Future Perspective and Conclusion

To improve the health of the soil, this review gives a general summary of how biochar contributes to soil biological activity and reduces plant heat stress. In light of the increased interest in the benefits of employing biochar as a nutrient and microbial carrier, as well as a C-based soil amendment, we suggest conducting the following study to enhance biochar's ability to support soil's biological health and ecological functions: Examine how biochar affects the development of durable microaggregates in different kinds of soil to assess how important these microaggregates are for housing soil microbial development. Investigate how biochar functions in various soil and environmental situations. Assess the real-world effects of biochar on agricultural productivity and its potential future applications. Highlight its shortcomings and offer potential solutions. Examine how carbon (C) and other nutrients are co-located in biochar produced using multiple feedstock types and consider their importance in enhancing microbial functions and activity. Analyse the presence and evolution of contaminants, including PTEs and PAHs, in biochar-derived sources using various feedstock types. These pollutants may impact the soil's biological health by preventing microbial development and function. Determine the extent to which biochar has immobilized soil pollution to mitigate microbial development and suppress activity.

Biochar soil amendment enhances water retention capacity, nutrient uptake efficiency, and cation exchange capacity, all of which contribute to improved plant health and productivity. The mechanism underlying the aforementioned potential is that it increases the quantity of organic matter and the root-zone surface area while altering the composition of the microbial community. Biochar is essential for mitigating heat stress and other climate change impacts because it reduces greenhouse gas emissions and promotes methanogen activity, thereby enhancing carbon storage [198]. A thorough analysis of the requirements for biochar should be conducted before application, as plant and soil reactions to biochar depend on its dosage, application technique, context (crop, soil chemistry, environment), pyrolysis temperature, and feedstock. A systematic study is necessary to determine how biochar interacts with various plant species and types of soil in diverse environmental settings.

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