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Role of Plant Growth Promoting Rhizobacteria (PGPR) and Biochar to Soil Carbon Sequestration and Plant Performance in Climate Resilience —A Review

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ABSTRACT

As the challenges associated with climate change continue to grow, focusing on sustainable and practical agricultural methods has become increasingly vital. One effective approach involves using biochar (BC) alongside PGPR, which is known to significantly boost plant performance and enhance carbon (C) sequestration. BC, created as a soil amendment, not only improves the physical and chemical characteristics of the soil but also aids in retaining moisture and preserving nutrients. By adding BC to the soil, a conducive environment for beneficial microorganisms can be established, thereby boosting their activity. This process can enhance the soil's capacity for C sequestration and improve its overall structure. Additionally, PGPR possesses unique abilities such as nitrogen fixation, phosphate solubilization, and hormone synthesis, which can enhance plant growth and performance, particularly in stressful conditions. These bacteria improve nutrient absorption and strengthen plants' resilience to environmental stressors, producing higher yields and better quality produce. In light of climate change, combining BC and PGPR offers a strategic advantage for enhancing agricultural resilience against the challenges posed by shifting weather patterns. This strategy not only aids in boosting crop production but also contributes significantly to reducing greenhouse gas emissions (GHG) through increased soil C sequestration, supporting sustainable development and environmental conservation initiatives.

***Keywords**:* Biochar, Carbon sequestration, Plant products, Growth-promoting bacteria

INTRODUCTION

The world's population is increasing and the need for food and soil and plant management and the use of environmentally friendly solutions to meet this need is necessary (Mirzaei Heydari et al., 2024; Mirzaei Heydari and Babaei 2022; Kadhim Joni Alsaedi et al., 2023). PGPR are bacteria that settle on the roots of plants and help plants grow. These bacteria can contribute to plant growth by directly enhancing water and mineral absorption, strengthening roots, interacting with other beneficial microorganisms to increase their effects on the plant, or suppressing plant pathogens through mechanisms such as phosphate solubilization, hormone production, or nitrogen fixation (Fathi *et al.,* 2017) Growth-promoting bacteria help plants achieve more significant growth and resilience under abiotic stresses and help reduce pollution. Additional information and a better understanding of bacterial properties that promote plant growth can motivate and inspire the development of innovative solutions that utilize PGPR under changing environmental and climatic conditions (Eyni *et al*., 2023). BC is commonly employed as a soil amendment to enhance soil quality by boosting water and nutrient retention, and it can potentially alter the composition of the soil microbial community (Ghadirnezhad Shiade *et al.,* 2023a). BC has been shown to improve soil fertility, enhance C sequestration in soil, and increase the diversity of soil microbial communities. This is attributed to its high porosity, large specific surface area, and cation exchange capacity (Ghadirnezhad Shiade *et al*., 2023a; Ghadirnezhad Shiade *et al.,* 2023b). Pyrolysis BC can be used as a potential soil amendment to improve soil physicochemical properties and crop yield, and the application of PGPR may increase soil microbial diversity and soil absorption (Ren *et al*., 2021; B. Singh *et al.,* 2014). On the other hand, it has been proven that plants face a variety of abiotic stresses such as drought, high ambient temperatures, salinity, light limitations, and lack of nutrients. These stresses can affect the growth and development of plants, and as a result, it is necessary to identify sustainable solutions that are in line with the environment for soil and plant management (Fathi *et al.,* 2024a, b, c,d; Shiade *et al.,* 2024a,b; Ghadirnezhad Shiade *et al.,* 2023a,b, 2024a,b). Finally, this study can help to better understand the interactions between BC, PGPR and soil in changing environments and provide new strategies to improve agriculture in the era of climate change.

The Impact of Climate Change and Global Warming

Today, agriculture faces numerous challenges, including the rise in the global population, which is expected to exceed eight billion by 2030. At the same time, climate change—primarily characterized by global warming and fluctuations in precipitation—may negatively affect crop production in many regions worldwide (Banerjee *et al*., 2021; Amin Fathi *et al*., 2020; Hafeez *et al*., 2023; Zamani *et al*., 2023). Climate change is increasingly recognized as a significant threat to agricultural production. As the global population grows, food security has become a major global issue, presenting a considerable challenge for scientists to overcome. Similarly, climate change poses substantial threats to meeting the demand for wheat consumption in light of rising population numbers and urbanization (Anwar *et al*., 2020; A Fathi, 2022; Fathi *et al*., 2024, 2023). Significant changes in precipitation and temperature have been identified at both regional and global levels, in terms of timing and intensity, as part of climate change. These changes affect agricultural inputs and outputs (Luo *et al*., 2018). The future of agricultural production is predicted to be markedly different from past and present conditions, with climate change emerging as a fundamental challenge in this area. In agriculture, climate change can have a significant impact on photosynthesis and plant production (Fathi, A., Shiade, S. R. G., Ait-El-Mokhtar, M., & Rajput, 2024). Since agricultural production is directly dependent on climatic conditions, agriculture is one of the first sectors to be affected by climate change (Fathi *et al*., 2020). While farmers cannot control or manage climatic conditions, effective management and adjustments in factors such as soil, irrigation, crop varieties, technologies, and activities used in cultivating crops can play a substantial role in mitigating the adverse effects of climate change on the performance, growth, and development of crops (Ghadirnezhad Shiade, Fathi, *et al*., 2024; Ghadirnezhad Shiade, Rahimi, *et al*., 2024; Hafeez *et al*., 2023; Shiade *et al*., 2024; Zamani *et al*., 2023).

Plant Growth Enhancing Bacteria

Soil biotechnology, which utilizes soil microorganisms, significantly impacts plant performance. This approach is particularly beneficial for soils with low organic matter and nutrient content, such as many soils in Iran. Currently, the use of soil microorganisms, especially PGPR, is on the rise. These bacteria play a crucial role in the nutrient cycling of soil and support plant growth by carrying out various biological processes (Mirzaei *et al*., 2018; Naseri *et al*., 2020). Furthermore, one of the strategies that has garnered attention for addressing drought stress is the inoculation of plants with various beneficial soil fungi and bacteria. These microorganisms enhance plant growth indicators either directly or indirectly through one or more specific mechanisms (Ghadirnezhad Shiade, Fathi, Taghavi Ghasemkheili, *et al*., 2023; Mirzaei Heydari *et al*., 2024; Mirzaei Heydari *et al*., 2024). In typical soil, the number of microbial cells can range from several million to several hundred million per gram of dry weight. These abundant soil microorganisms are unevenly distributed throughout the soil, primarily located in nutrient-rich micropores that provide ideal growth conditions. The distribution of bacteria is significantly more uneven in vegetative soil than soil without plants; in the rhizosphere, the conditions lead to a distinct diversity and abundance of bacteria compared to non-rhizosphere soil (Gamalero *et al*., 2015). In 1904, Hiltner described the rhizosphere as a narrow region (1 to 2 mm thick) of soil surrounding plant roots, influenced by the root system. Releasing various organic compounds from the roots often results in high microbial density and activity in the rhizosphere, making it a primary site for microbial activity and colonization. Generally, soil microorganisms found in the rhizosphere can be categorized as harmful, beneficial, or neutral based on their effects on plants. It has been estimated that approximately two to five percent of the bacteria present in the rhizosphere possess physiological traits that contribute to enhancing plant growth (Gamalero *et al*., 2015). Rhizosphere bacteria that promote plant growth are beneficial, non-symbiotic microorganisms capable of enhancing plant growth either directly or indirectly through specific mechanisms. These growth-promoting bacteria have been recognized for their ability to improve plant growth and productivity upon inoculation. A diverse range of soil bacteria can function as PGPR. These beneficial bacteria help mitigate the negative impacts of biotic and abiotic stresses on plants. They achieve this by altering the root architecture of host plants through the production of growth hormones such as auxins, cytokinins, and gibberellic acid; synthesizing the enzyme ACC-deaminase; inducing systemic resistance; and facilitating biochemical and morphological changes. Additionally, they promote the expression of stress response genes, produce extracellular polysaccharides, form biofilms, generate organic signaling compounds, and regulate osmotic pressure in plant interactions with rhizosphere bacteria, all contributing to drought stress tolerance in plants (Bagheri *et al*., 2020; Mohammad Mirzaei Heydari *et al*., 2022; Najim Abdul Reda *et al*., 2024; Shintu *et al*., 2015). The primary objective of advancing biotechnology focused on PGPR is to boost the population of beneficial bacteria in the soil. This enhancement can contribute to sustainable agriculture and decrease the reliance on pesticides and chemical fertilizers.

Mechanisms of BC for C Sequestration

The impact of BC on C sequestration involves various interconnected processes. Each of these processes plays a part in the overall soil C sequestration, and their contrasting effects lead to enhanced C storage in the soil. Below, we explore some of the mechanisms associated with the role of BC in C sequestration.

Increased Soil Organic C (SOC) Input

When BC is introduced to the soil, it serves as a stable form of C, offering a long-lasting source of organic C (Leng *et al*.,2019). Its resistance to decay enables it to remain in the soil for extended periods, effectively enhancing the overall input of soil organic C (SOC) (Ma *et al*.,2022). The potential for C sequestration from BC is influenced by its stability in the soil and its priming effect on the mineralization of native soil organic C, which can be affected by factors such as the processing of BC, its age, and the clay content of the soil (Yang, Sun, Han, *et al*.,2022). Research shows that adding BC to acidic soils increases pH and enhances soil fertility, potentially boosting plant yields and promoting C bio-sequestration from the atmosphere through photosynthesis (Yang, Sun, Han, *et al*.,2022). After the addition of BC, the organic C derived from it can integrate with existing SOC. Depending on the conditions under which BC is produced and the characteristics of the soil (like clay content and temperature), studies have shown that approximately80–97% of BC's organic C can remain unmineralized as CO2 for hundreds to thousands of years (Bruun *et al*.,2014; Farrell *et al*.,2013; Han *et al*.,2020; Keith *et al*.,2011; B. T. Nguyen *et al*.,2014). This stable fraction of organic C from BC not only increases the overall organic C content but also modifies the composition of soil organic C through physical mixing (Han *et al*.,2020). A global meta-analysis included64 studies with736 individual treatments from field experiments that lasted between1 and10 years, involving BC applications of1 to100 Mg ha−1 (Gross *et al*.,2021). It was found that there was an average increase of13.0 Mg ha−1 in soil organic C stocks, representing a29% rise. Pot and incubation experiments varied from1 to1278 days with BC amounts spanning from5 g kg−1 to200 g kg−1, resulting in an average SOC increase of6.3 g kg−1, equivalent to75%. More SOC accumulation was observed in longer experimental durations exceeding500 days in pot and incubation studies and6–10 years in field studies than in shorter ones. BC derived from plant materials demonstrated a higher C sequestration potential compared to that from fecal matter, attributed to a greater C-to-nitrogen ratio (Gross *et al*.,2021). Increases in SOC following BC application were more pronounced in medium to fine-textured soils compared to coarse-textured soils. This study clearly highlighted the significant C sequestration potential of BC applications in agricultural soils with diverse characteristics (Gross *et al*.,2021).

Protection against Microbial Decomposition

BC is essential in physically protecting labile organic C, such as rhizodeposits and microbial necromass, from microbial decomposition (S. H. Vetter *et al*.,2022). Its resilient structure and exceptional stability create a barrier that safeguards the organic C contained within from microbial activity (Palviainen *et al*.,2018). This protective role significantly lowers the rate of C mineralization, resulting in the accumulation of soil organic C (SOC) (Lorenz *et al*.,2014). Researchers (Cheng *et al*.,2017) examined the effects of BC produced at various temperatures and torrefied biomass on the breakdown of simple C substrates (like glucose and amino acids), plant residues (such as *Lolium perenne L.*), and native soil organic matter (SOM) using a14C labeling technique. Their study involved incorporating torrefied biomass and BC made from wheat straw at four different pyrolysis temperatures (250,350,450, and550 °C) into sandy loam soil, and they assessed how these additions affected C turnover compared to untreated soil or soil amended with unprocessed straw. They observed that the addition of BC, torrefied biomass, and straw caused shifts in the soil microbial community's size, activity, and structure, with the most significant changes occurring in the soil treated with straw. Furthermore, these additions altered microbial C use efficiency (CUE), leading to a greater portion of substrate C being directed toward catabolic processes. Overall, while the addition of BC, torrefied biomass, and straw increased soil respiration, it reduced the turnover rates of simple C substrates, plant residues, and native SOM, with no significant effect on microbial biomass turnover (Cheng *et al*.,2017). The negative priming effect on SOM was found to positively correlate with the temperature at which BC was produced. Compared to straw, BC showed the most potential for enhancing soil C storage, although straw and torrefied biomass may offer additional benefits that could make them more advantageous for CO2 reduction strategies (Cheng *et al*.,2017).

Enhanced Soil Aggregation

BC has a notable ability to improve soil aggregation, which is the process of creating cohesive clumps or aggregates of soil (Y. Li *et al*.,2018). The application of BC can influence the size distribution of these soil aggregates (Y. Chen *et al*.,2024). Generally, studies have shown that BC positively affects soil aggregation in both laboratory settings and field experiments (Yang, Sun, Liu, *et al*.,2022). Several mechanisms have been suggested to explain the increase in soil aggregation following BC application: (1) the oxygen-containing functional groups on the surface of BC can interact with soil organo-mineral complexes, enhancing the stability of soil aggregates; (2) BC has a large surface area and numerous pores that can absorb root exudates and boost microbial biomass, which may act as binding agents to facilitate soil aggregation; (3) the increased hydrophobicity of the soil due to BC may reduce clay swelling and prevent aggregate disruption, thereby improving aggregate stability (Y. Chen *et al*.,2024).Fourier-transform infrared (FTIR) spectroscopy analysis revealed that in soils with low soil organic C (SOC) content, the addition of BC resulted in an enrichment of aromatic C, carboxyl C, and small amounts of ketones and esters. These changes were mainly observed in the unprotected organic matter and aggregates (Weng *et al*.,2022). The findings provide strong evidence that BC not only demonstrates high stability but also effectively outperforms the addition of labile organic matter, such as green manure, in stabilizing C (Weng *et al*.,2022). It is crucial to recognize that the interactions between BC and various soil types and structures can lead to differing effects, which require further exploration (S. Li *et al*.,2023). Different responses were noted with varying amounts of BC applied to distinct soil types, affecting wet aggregate stability differently (Hu *et al*.,2018). In sandy loam soils, the addition of BC increased soil surface area, compensating for the initially low SOC content and facilitating SOC-induced aggregation (Hu *et al*.,2018). In contrast, in clay soils, a higher application rate of BC (40 t ha^{-1}) intensified repulsive forces between similarly charged particles and monovalent cations, resulting in chemical disturbances and some aggregate breakdown, which was not found with a lower BC dosage (20 t ha^{-1}) (Hu *et al*.,2018). Additionally, the pore structure of clay aggregates was modified, showing a rise in micropores (30–5 μm, increased by29% compared to the control) and ultramicropores (5–0.1 μm, increased by22% compared to the control) following BC addition, contributing to aggregate stability (Hu *et al*.,2018). Overall, these outcomes highlight the beneficial impact of BC on aggregate stability, enhancing the physical fertility of soils, particularly those with coarse textures and low organic C content (S. Li *et al*.,2023).

Increased Water and Nutrient Retention

BC has a high cation exchange capacity (CEC) and moderate alkalinity, which enables it to attract and retain water and nutrients, particularly nitrogen (N) and potassium (K), within the soil (S. Li *et al*.,2018; Liao *et al*.,2019). By holding onto water and nutrients such as nitrogen and phosphorus, BC enhances nutrient availability for plants and minimizes nutrient loss from the soil system (Khadem *et al*.,2021; Rogovska *et al*.,2014). This increased nutrient availability supports greater plant growth and productivity, which, in turn, contributes organic C to the soil through root exudates, rhizodeposition, and plant residues (Domingues *et al*.,2020; Pituello *et al*.,2018). The surface area, porosity, and ion exchange capacity of certain BCs likely influence their ability to absorb and potentially release organic matter (OM) or nutrients over time (Fahad *et al*.,2022). However, Mukherjee *et al*. (2011) noted that the CEC of BC varied from0 to70 cmol kg−1 in samples produced at lower temperatures. They also found that aged BCs contained significant amounts of anion exchange capacity (AEC), suggesting that fresh BC should be effective at retaining ammonia (NH4+) while releasing exchangeable nitrate (NO3−) and phosphate (PO43−). Wu *et al*. (2011) reported that there was no clear relationship between BET surface area and catalytic activity, indicating substantial changes in C structure. T. T. N. Nguyen *et al*. (2017) noted that the BRT model indicated a significant correlation between BC CEC and NH4+-N adsorption. Variations in lignin, cellulose, and hemicellulose influenced the physical characteristics of BC, affecting nutrient release. BC has been utilized as a soil amendment to enhance soil's water retention capabilities due to its porous structure (Bikbulatova *et al*.,2018). The water holding capacity and rate of water adsorption have been found to correlate directly with the micropore volume of BC, suggesting that its physical structure plays a crucial role in water interaction (Bikbulatova *et al*.,2018).In a study, Razzaghi *et al*. (2020) performed a statistical meta-analysis of studies published between2010 and2019 to assess the effects of BC on soil bulk density (BD) and various water retention metrics—specifically, soil water content at field capacity (FC), wilting point (WP), and available water content (AW). On average, BC application reduced BD by9% across all soil types. FC and WP significantly increased in coarse-textured soils (by51% and47%, respectively) and moderately in medium-textured soils (by13% and9%, respectively). In fine-textured soils, FC remained relatively unchanged (<1%), while WP slightly decreased by5%. Additionally, BC significantly enhanced AW in coarse-textured soils (by45%) compared to medium- (21%) and fine-textured soils (14%), indicating that BC may provide more benefits to coarse-textured soils (Razzaghi *et al*.,2020). In summary, the surface properties of BC positively impact soil nutrients and cation availability (Ennis *et al*.,2012). Co-adsorption may lead to higher local nutrient concentrations for microbial communities and improved water retention, while the adsorption of organic matter reduces runoff losses. However, there may also be competing negative effects on nutrient availability for plants and signaling between microorganisms and plants caused by sorption (Ennis *et al*.,2012).

Altered Soil Microbial Community

Changes in the quality and rates of organic substrates due to the aging of BC may lead to shifts in soil microbial communities, both at the individual level and among different physiological groups of microbes, potentially affecting the kinetics of C assimilation pathways (Button,1993; Hobbie *et al*.,2012). Theoretically, the C uptake by soil microorganisms should energetically cover the metabolic costs associated with substrate uptake mechanisms (Sinsabaugh *et al*.,2010), and the optimal level of substrate saturation should remain constant. In conditions of low C availability, this can disrupt the balance between catabolic and anabolic processes, resulting in lower C use efficiency (CUE) across soil microbial communities (Manzoni *et al*.,2009).CUE at the microbial community level is influenced by several ecological factors, including the type and bioavailability of C sources, the relative abundance of different microbial physiological groups, soil moisture, and temperature, typically decreasing with soil depth (Dijkstra *et al*.,2011; Spohn *et al*.,2016). At the individual microbial level, CUE values fluctuate based on the physiological state of the microorganisms; they tend to be lower during the C assimilation phase and higher during the exponential growth phase (Robinson,2008). This variation occurs because microorganisms quickly respire C after exposure to energy substrates, leading to the synthesis of extracellular enzymes for soil organic matter (SOM) decomposition and cell membrane transport proteins. In contrast, during the logarithmic growth phase, the assimilated C is primarily directed towards building new biomass (Schimel *et al*.,2003; Y. A. Vetter *et al*.,1998). Research has shown that the soil microbial community composition changes after BC amendment, with increases in microbial abundance reported in a dose-dependent manner (He *et al*.,2021). For instance, an increase in fungal populations following BC application in alkaline soils was noted, indicating that the impact of BC is influenced by the specific type of BC and soil characteristics (Gao *et al.*,2021). The addition of BC at rates between10–15% w:w led to modifications in the microbial community structure and a significant rise in the richness and diversity indices of total microbes (K. Chen *et al*.,2020). Conversely, a short-term study found no significant changes in microbial community structure or extracellular enzyme activities when comparing BC application (22 t ha−1) to manure amendment (Elzobair *et al*.,2016).

Stabilization of Labile C

BC stabilizes labile C through several essential mechanisms. Firstly, BC has a resilient and stable structure that serves as a physical barrier, protecting labile C from microbial decomposition (Fang *et al.*,2014). Its porous characteristics create an environment that slows the rate of C mineralization, thereby extending the residence time of labile C in the soil (Lorenz *et al.*,2014). Secondly, BC has a large surface area that allows it to adsorb organic compounds (Zhu *et al.*,2020). Labile C molecules can adhere to the surface of BC particles, forming stable bonds that decrease their vulnerability to microbial degradation (Ghosh *et al.*,2023). This sorption mechanism effectively keeps labile C in the soil, hindering its rapid breakdown. Furthermore, BC influences chemical interactions, promotes aggregate formation, and alters microbial community dynamics, all of which contribute to the stabilization of labile C in the soil (Hu *et al.,*2018; Jung *et al.,*2019; N. Singh *et al.,*2009). These processes result in the creation of more stable C compounds, enhancing the sequestration of labile C (S. Li *et al*.,2023).

CONCLUSION

Combining PGPR with BC presents a promising strategy to boost soil C sequestration and enhance plant yields in the context of climate change challenges. The synergistic benefits of

BC as a soil amendment, alongside the advantageous traits of PGPR, contribute to improved soil health and nutrient availability, both of which are vital for sustainable agricultural practices. Additionally, PGPR enhances nutrient uptake and crop resilience, resulting in increased productivity and quality—an aspect that is particularly important in response to unpredictable environmental stresses. This dual approach not only maximizes agricultural output but also plays a significant role in mitigating GHG, thereby aiding global initiatives for environmental preservation and sustainable development. As climate-related challenges grow more severe, it is essential to leverage the capabilities of BC and PGPR to develop resilient agricultural systems that ensure food security while upholding environmental sustainability.

Declaration of generative AI in scientific writing

During the preparation of this work the author(s) used [ChatGPT] in order to [improve and edit the text]. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

REFERENCES

Anwar A., Younis M., Ullah I. 2020. Impact of urbanization and economic growth on CO2 emission: a case of far east Asian countries. *International Journal of Environmental Research and Public Health*, *17*(7), 2531.

Bagheri M., Mirzaei Heydari M. 2020. Effect of Biofertilizers and Chemical Fertilizers on Phosphorus Uptake and Wheat Yield. *Research On Crop Ecophysiology*, *15*(1), 13–19.

Banerjee A., Chen R., Meadows M. E., Sengupta D., Pathak S., Xia Z., Mal S. 2021. Tracking 21st century climate dynamics of the Third Pole: An analysis of topo-climate impacts on snow cover in the central Himalaya using Google Earth Engine. *International Journal of Applied Earth Observation and Geoinformation*, *103*, 102490.

Bikbulatova S., Tahmasebi A., Zhang Z., Rish S. K., Yu J. 2018. Understanding water retention behavior and mechanism in bio-char. *Fuel Processing Technology*, *169*, 101–111.

Bruun S., Clauson Kaas, S., Bobuľská L., Thomsen I. K. 2014. Carbon dioxide emissions from biochar in soil: role of clay, microorganisms and carbonates. *European Journal of Soil Science*, *65*(1), 52–59.

Button D. K. 1993. Nutrient-limited microbial growth kinetics: overview and recent advances. *Antonie van Leeuwenhoek*, *63*, 225–235.

Chen K., Peng J., Li J., Yang Q., Zhan X., Liu N., Han X. 2020. Stabilization of soil aggregate and organic matter under the application of three organic resources and biochar-based compound fertilizer. *Journal of Soils and Sediments*, *20*, 3633–3643.

Chen Y., Sun K., Yang Y., Gao B., Zheng H. 2024. Effects of biochar on the accumulation of necromass-derived carbon, the physical protection and microbial mineralization of soil organic carbon. *Critical Reviews in Environmental Science and Technology*, *54*(1), 39–67.

Cheng H., Hill P. W., Bastami M. S., Jones D. L. 2017. Biochar stimulates the decomposition of simple organic matter and suppresses the decomposition of complex organic matter in a sandy loam soil. *GCB Bioenergy*, *9*(6), 1110–1121.

Dijkstra P., Thomas S. C., Heinrich P. L., Koch G. W., Schwartz E., Hungate B. A. 2011. Effect of temperature on metabolic activity of intact microbial communities: evidence for altered metabolic pathway activity but not for increased maintenance respiration and reduced carbon use efficiency. *Soil Biology and Biochemistry*, *43*(10), 2023–2031.

Domingues R. R., Sánchez-Monedero M. A., Spokas K. A., Melo L. C. A., Trugilho P. F., Valenciano M. N., Silva C. A. 2020. Enhancing cation exchange capacity of weathered soils using biochar: feedstock, pyrolysis conditions and addition rate. *Agronomy*, *10*(6), 824.

Elzobair K. A., Stromberger M. E., Ippolito J. A., Lentz R. D. 2016. Contrasting effects of biochar versus manure on soil microbial communities and enzyme activities in an Aridisol. *Chemosphere*, *142*, 145–152.

Ennis C. J., Evans A. G., Islam M., Ralebitso-Senior T. K., Senior E. 2012. Biochar: carbon sequestration, land remediation, and impacts on soil microbiology. *Critical Reviews in Environmental Science and Technology*, *42*(22), 2311–2364.

Eyni H., Mirzaei Heydari M., Fathi A. 2023. Investigation of the application of urea fertilizer, mycorrhiza, and foliar application of humic acid on quantitative and qualitative properties of canola. *Crop Science Research in Arid Regions*, *4*(2), 405–420.

Fahad S., Chavan S. B., Chichaghare A. R., Uthappa A. R., Kumar M., Kakade V., Pradhan A., Jinger D., Rawale G., Yadav D. K. 2022. Agroforestry systems for soil health improvement and maintenance. *Sustainability*, *14*(22), 14877.

Fang Y., Singh B., Singh B. P., Krull E. 2014. Biochar carbon stability in four contrasting soils. *European Journal of Soil Science*, *65*(1), 60–71.

Farrell M., Kuhn T. K., Macdonald L. M., Maddern T. M., Murphy D. V, Hall P. A., Singh B. P., Baumann K., Krull E. S., Baldock J. A. 2013. Microbial utilisation of biochar-derived carbon. Science of the Total Environment, 465, 288–297.

Fathi A, Mehdiniyaafra J. 2023. Plant Growth and Development in Relation to Phosphorus: A review. *Bulletin of the University of Agricultural Sciences & Veterinary Medicine Cluj-Napoca. Agriculture*, *80*(1).

Fathi A, Barari Tari D., Fallah Amoli H., Niknejad Y. 2020. Study of energy consumption and greenhouse gas (GHG) emissions in corn production systems: influence of different tillage systems and use of fertilizer. *Communications in Soil Science and Plant Analysis*, *51*(6), 769–778.

Fathi A. 2022. Role of nitrogen (N) in plant growth, photosynthesis pigments, and N use efficiency: a. *Agrisost*, *28*, 1–8.

Fathi A., Shiade S. R. G., Ait-El-Mokhtar M., Rajput V. D. 2024a. Crop Photosynthesis under Climate Change. In Handbook of Photosynthesis (4th ed.). Taylor & Francis, Boca Raton, USA. pp 826. https://doi.org/10.1201/b22922

Fathi A., Shiade S. R. G., Ali B., Zeidali E. 2024b. Plant Growth, Development, and Photosynthesis in Cereals under Salt Stress. In Handbook of Photosynthesis (4th ed.). Taylor & Francis, Boca Raton, USA. pp 826. https://doi.org/10.1201/b22922

Fathi A., Shiade S. R. G., Kianersi F., Altaf M. A., Amiri E., Nabati E. 2024c. Photosynthesis in Cereals under Drought Stress. In Handbook of Photosynthesis (4th ed.). Taylor & Francis, Boca Raton, USA. pp 826. https://doi.org/10.1201/b22922

Fathi A., Shiade S. R. G., Parmoon G., Yaghoubian Y., Pirdashti H., Rajput V. D., Minkina T. (2024d). Bioremediation of heavy metals contaminated soils using nanotechnology. In Bio-organic Amendments for Heavy Metal Remediation (pp. 611-628). Elsevier.

Fathi A., Shiade S. R. G., Zahra N., Farooq M. 2024e. Photosynthesis in Plants under Cold Stress. In Handbook of Photosynthesis (4th ed.). Taylor & Francis, Boca Raton, USA. pp 826. https://doi.org/10.1201/b22922

Gamalero E., Glick B. R. 2015. Bacterial modulation of plant ethylene levels. *Plant Physiology*, *169*(1), 13–22.

Gao W., Gao K., Guo Z., Liu Y., Jiang L., Liu C., Liu X., Wang G. 2021. Different responses of soil bacterial and fungal communities to 3 years of biochar amendment in an alkaline soybean soil. *Frontiers in Microbiology*, *12*, 630418.

Ghadirnezhad Shiade S. R., Fathi A., Kardoni F., Pandey R., Pessarakli M. 2024b. Nitrogen contribution in plants: recent agronomic approaches to improve nitrogen use efficiency. *Journal of Plant Nutrition*, *47*(2), 314–331.

Ghadirnezhad Shiade S. R., Fathi A., Minkina T., Wong M. H., Rajput V. D. 2023a. Biochar application in agroecosystems: a review of potential benefits and limitations. *Environment, Development and Sustainability, 0123456789*. doi: 10.1007/s10668-023-03470-z

Ghadirnezhad Shiade S. R., Fathi A., Taghavi Ghasemkheili F., Amiri E., Pessarakli M. 2023b. Plants' responses under drought stress conditions: Effects of strategic management approaches—a review. *Journal of Plant Nutrition*, *46*(9), 2198–2230. doi: 10.1080/01904167.2022.2105720

Ghadirnezhad Shiade S. R., Rahimi R., Zand-Silakhoor A., Fathi A., Fazeli A., Radicetti E., Mancinelli R. 2024a. Enhancing Seed Germination Under Abiotic Stress: Exploring the Potential of Nano-Fertilization. *Journal of Soil Science and Plant Nutrition*, 1–23.

Ghosh D., Maiti S. K. 2023. Invasive weed based biochar facilitated the restoration of coal mine degraded land by modulating the enzyme activity and carbon sequestration. *Restoration Ecology*, *31*(3), e13744.

Gross A., Bromm T., Glaser B. 2021. Soil organic carbon sequestration after biochar application: A global meta-analysis. *Agronomy*, *11*(12), 2474.

Hafeez A., Ali B., Javed M. A., Saleem A., Fatima M., Fathi A., Afridi M. S., Aydin V., Oral M. A., Soudy F. A. 2023. Plant breeding for harmony between sustainable agriculture, the environment, and global food security: an era of genomics assisted breeding. *Planta*, *258*(5), 97.

Han L., Sun K., Yang Y., Xia X., Li F., Yang Z., Xing B. 2020. Biochar's stability and effect on the content, composition and turnover of soil organic carbon. *Geoderma*, *364*, 114184.

He X., Xie H., Gao D., Khashi U. Rahman M., Zhou X., Wu F. 2021. Biochar and intercropping with potato–onion enhanced the growth and yield advantages of tomato by regulating the soil properties, nutrient uptake, and soil microbial community. *Frontiers in Microbiology*, *12*, 695447.

Hobbie J. E., Hobbie, E. A. 2012. Amino acid cycling in plankton and soil microbes studied with radioisotopes: measured amino acids in soil do not reflect bioavailability. *Biogeochemistry*, *107*, 339–360.

Hu F., Liu J., Xu C., Du W., Yang Z., Liu X., Liu, G., Zhao S. 2018. Soil internal forces contribute more than raindrop impact force to rainfall splash erosion. *Geoderma*, *330*, 91–98.

Jung S., Park Y.-K., Kwon E. E. 2019. Strategic use of biochar for CO2 capture and sequestration. *Journal of CO2 Utilization*, *32*, 128–139.

Keith A., Singh B., Singh B. P. 2011. Interactive priming of biochar and labile organic matter mineralization in a smectite-rich soil. *Environmental Science & Technology*, *45*(22), 9611–9618.

Khadem A., Raiesi F., Besharati H., Khalaj M. A. 2021. The effects of biochar on soil nutrients status, microbial activity and carbon sequestration potential in two calcareous soils. *Biochar*, *3*, 105–116.

Leng L., Xu X., Wei L., Fan L., Huang H., Li J., Lu Q., Li J., Zhou W. 2019. Biochar stability assessment by incubation and modelling: Methods, drawbacks and recommendations. *Science of the Total Environment*, *664*, 11–23.

Li S., Chen G. 2018. Thermogravimetric, thermochemical, and infrared spectral characterization of feedstocks and biochar derived at different pyrolysis temperatures. *Waste Management*, *78*, 198–207.

Li S., Tasnady D. 2023. Biochar for soil carbon sequestration: Current knowledge, mechanisms, and future perspectives. *C*, *9*(3), 67.

Li Y., Li Y., Chang S. X., Yang Y., Fu S., Jiang P., Luo Y., Yang M., Chen Z., Hu S. 2018. Biochar reduces soil heterotrophic respiration in a subtropical plantation through increasing soil organic carbon recalcitrancy and decreasing carbon-degrading microbial activity. *Soil Biology and Biochemistry*, *122*, 173–185.

Liao W., Thomas S. C. 2019. Biochar particle size and post-pyrolysis mechanical processing affect soil pH, water retention capacity, and plant performance. *Soil Systems*, *3*(1), 14.

Lorenz K., Lal R. 2014. Biochar application to soil for climate change mitigation by soil organic carbon sequestration. *Journal of Plant Nutrition and Soil Science*, *177*(5), 651–670.

Luo Q., O'Leary G., Cleverly J., Eamus D. 2018. Effectiveness of time of sowing and cultivar choice for managing climate change: wheat crop phenology and water use efficiency. *International Journal of Biometeorology*, *62*, 1049–1061.

Ma S., Wang X., Wang S., Feng K. 2022. Effects of temperature on physicochemical properties of rice straw biochar and its passivation ability to Cu2+ in soil. *Journal of Soils and Sediments*, *22*(5), 1418–1430.

Manzoni S., Porporato A. 2009. Soil carbon and nitrogen mineralization: Theory and models across scales. *Soil Biology and Biochemistry*, *41*(7), 1355–1379.

Mirzaei Heydari M, Babaei Z. 2022. The effect of plant growth promoting bacteria inoculated in soil and different rates of phosphorous fertilizer on growth and yield of autumn wheat. *Iranian Journal of Soil and Water Research*, *53*(10), 2247–2259.

Mirzaei Heydari M, Brook R. M., Jones D. L. 2024. Barley Growth and Phosphorus Uptake in Response to Inoculation with Arbuscular Mycorrhizal Fungi and Phosphorus Solubilizing Bacteria. *Communications in Soil Science and Plant Analysis*, *55*(6), 846–861.

Mirzaei Heydari M, Fathi A., Atashpikar R. 2024. The effect of chemical and biofertilizer on the nutrient concentration of root, shoot and seed of bean (*Phaseolus vulgaris* L.) under drought stress. *Crop Science Research in Arid Regions*, *5*(3), 539–554.

Mirzaei A., Naseri R., Torab Miri S. M., Soleymani Fard A., Fathi A. 2018. Reaspose of Yield and Yield Components of Chickpea (*Cicer arietinum* L.) Cultivars to the Application of Plant Growth Promoting RhizohBacteria and Nitrogen Chemical Fertilizer under Rainfed Conditions. *Journal of Crop Ecophysiology*, *11*(44(4)), 775–790. Retrieved from https://jcep.tabriz.iau.ir/article_539518.html

Mukherjee A., Zimmerman A. R., Harris, W. 2011. Surface chemistry variations among a series of laboratory-produced biochars. *Geoderma*, *163*(3–4), 247–255.

Najim Abdul Reda M., Mirzaei Heydari M. 2024. Evaluation the effect of mycorrhizal inoculation and different amounts of sheep manure on the quantitative and qualitative yield of mung bean cultivars. *Iranian Journal of Soil and Water Research*.

Naseri R., Soleymani F. A., Mirzaeir A., Darabi F., Fathi A. 2020. The effect of Plant Growth Promoting Rhizohacteria on activities of antioxidative enzymes, physiological characteristics and root growth of four chickpea (*Cicer arietinum* L.) cultivars under dry land conditions of Ilam privince. *Iranian Journal Pulses Research*, *10*(2), 62–76.

Nguyen B. T., Koide R. T., Dell C., Drohan P., Skinner H., Adler P. R., Nord A. 2014. Turnover of soil carbon following addition of switchgrass- derived biochar to four soils. *Soil Science Society of America Journal*, *78*(2), 531–537.

Nguyen T. T. N., Xu C.-Y., Tahmasbian I., Che R., Xu Z., Zhou X., Wallace H. M., Bai S. H. 2017. Effects of biochar on soil available inorganic nitrogen: a review and meta-analysis. *Geoderma*, *288*, 79–96.

Palviainen M., Berninger F., Bruckman, V. J., Köster K., de Assumpção C. R. M., Aaltonen H., Makita N., Mishra A., Kulmala L., Adamczyk B. 2018. Effects of biochar on carbon and nitrogen fluxes in boreal forest soil. *Plant and Soil*, *425*, 71–85.

Pituello C., Dal Ferro N., Francioso O., Simonetti G., Berti A., Piccoli I., Pisi A., Morari F. 2018. Effects of biochar on the dynamics of aggregate stability in clay and sandy loam soils. *European Journal of Soil Science*, *69*(5), 827–842.

Razzaghi F., Obour P. B., Arthur, E. 2020. Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma*, *361*, 114055.

Ren H., Lv C., Fernández-García V., Huang B., Yao J., Ding W. 2021. Biochar and PGPR amendments influence soil enzyme activities and nutrient concentrations in a eucalyptus seedling plantation. *Biomass Conversion and Biorefinery*, *11*, 1865–1874.

Robinson C. 2008. Heterotrophic bacterial respiration. In Microbial ecology of the oceans (pp. 299–334). Wiley.

Rogovska N., Laird D. A., Rathke S. J., Karlen D. L. 2014. Biochar impact on Midwestern Mollisols and maize nutrient availability. *Geoderma*, *230*, 340–347.

Schimel J. P., Weintraub M. N. 2003. The implications of exoenzyme activity on microbial carbon and nitrogen limitation in soil: a theoretical model. *Soil Biology and Biochemistry*, *35*(4), 549–563.

Shiade S. R. G., Fathi A., Rahimi R., DahPahlavan S. 2024a. Crop Adaptation to Climate Change: Improvements in Photosynthesis. In Handbook of Photosynthesis (pp. 676-684). Taylor Francis, Boca Raton, USA. pp 826. https://doi.org/10.1201/b22922

Shiade S. R. G., Zand-Silakhoor A., Fathi A., Rahimi R., Minkina T., Rajput V. D., Zulfiqar, U., Chaudhary T. 2024b. Plant Metabolites and Signaling Pathways in Response to Biotic and Abiotic Stresses: Exploring Bio stimulant Applications. *Plant Stress*, 100454.

Shintu P. V, Jayaram, K. M. 2015. Phosphate solubilising bacteria (Bacillus polymyxa)-An effective approach to mitigate drought in tomato (Lycopersicon esculentum Mill.). *Trop. Plant Res*, *2*(1), 2349–9265.

Singh B., Macdonald L. M., Kookana R. S., van Zwieten L., Butler G., Joseph S., Weatherley A., Kaudal B. B., Regan A., Cattle J. 2014. Opportunities and constraints for biochar technology in Australian agriculture: looking beyond carbon sequestration. *Soil Research*, *52*(8), 739–750.

Singh N., Kookana R. S. 2009. Organo-mineral interactions mask the true sorption potential of biochars in soils. *Journal of Environmental Science and Health Part B*, *44*(3), 214–219.

Sinsabaugh R. L., Shah J. J. F. 2010. Integrating resource utilization and temperature in metabolic scaling of riverine bacterial production. *Ecology*, *91*(5), 1455–1465.

Spohn M., Klaus K., Wanek W., Richter A. 2016. Microbial carbon use efficiency and biomass turnover times depending on soil depth–Implications for carbon cycling. *Soil Biology and Biochemistry*, *96*, 74–81.

Vetter S. H., Abdalla M., Kuhnert M., Smith, P. 2022. Soil Carbon Sequestration and Biochar. *Greenhouse Gas Removal Technologies*, *31*, 194.

Vetter Y. A., Deming J. W., Jumars P. A., Krieger-Brockett B. B. 1998. A predictive model of bacterial foraging by means of freely released extracellular enzymes. *Microbial Ecology*, *36*, 75–92.

Weng Z., Van Zwieten L., Tavakkoli E., Rose M. T., Singh B. P., Joseph S., Macdonald L. M., Kimber S., Morris S., Rose T. J. 2022. Microspectroscopic visualization of how biochar lifts the soil organic carbon ceiling. *Nature Communications*, *13*(1), 5177.

Wu G., Nelson M., Ma S., Meng H., Cui G., Shen P. K. 2011. Synthesis of nitrogen-doped onion-like carbon and its use in carbon-based CoFe binary non-precious-metal catalysts for oxygen-reduction. *Carbon*, *49*(12), 3972–3982.

Yang Y., Sun K., Han L., Chen Y., Liu J., Xing B. 2022. Biochar stability and impact on soil organic carbon mineralization depend on biochar processing, aging and soil clay content. *Soil Biology and Biochemistry*, *169*, 108657.

Yang Y., Sun K., Liu J., Chen Y., Han L. 2022. Changes in soil properties and CO2 emissions after biochar addition: Role of pyrolysis temperature and aging. *Science of the Total Environment*, *839*, 156333.

Zamani Z., Zeidali E., Alizadeh H. A., Fathi A. 2023. Effect of drought stress and nitrogen chemical fertilizer on root properties and yield in three quinoa cultivars (Chenopodium quinoa Willd). *Crop Science Research in Arid Regions*, *5*(2), 487–500.

Zhu Y., Yi B., Hu H., Zong Z., Chen M., Yuan Q. 2020. The relationship of structure and organic matter adsorption characteristics by magnetic cattle manure biochar prepared at different pyrolysis temperatures. *Journal of Environmental Chemical Engineering*, *8*(5), 104112.