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THE SYNERGISTIC ROLE OF BIOCHAR AND PLANT GROWTH-PROMOTING RHIZOBACTERIA IN MANAGING ENVIRONMENTAL STRESS IN FIELD CROPS: A REVIEW

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Abstract

The world climate is undergoing significant changes due to the extensive release of greenhouse gases. These emissions lead to environmental challenges such as drought, salinity, and heavy metal contamination which have a long-lasting impact on food security, particularly in developing countries. This requires identifying ecologically sustainable and economically efficient methods to tackle these environmental stresses. Biochar has many distinctive attributes that enhance its efficacy, cost-effectiveness, and ecological compatibility. They include its ability to improve soil health, promote crop growth and production, and regulate nutrient dynamics via features that maintain microbial life. Biochar has a substantial amount of organic carbon, is rich in nutrients like nitrogen (N), phosphorus (P), and potassium (K), exhibits a high degree of porosity, and demonstrates a remarkable ability to retain water. Plant growth-promoting rhizobacteria (PGPR) function as a co-evolutionary process between plants and microbes, displaying both antagonistic and synergistic interactions with microorganisms and soil. This review emphasizes the significance of synergistically using biochar and PGPR to enhance soil quality and agricultural production in both optimal and challenging environments, provided they are mutually beneficial. The implementation of this approach enhances the effectiveness of resource conservation, alleviates both biotic and abiotic stresses, and ultimately mitigates the impacts of climate change.

Keywords: Biochar, Plant growth-promoting rhizobacteria, Biotic stress, Abiotic stress.

الدور التآزري للفحم الحيوي والبكتيريا الجذرية المحفزة لنمو النباتات في إدارة الشدود البيئية في المحاصيل الحقلية: مراجعة مقال

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الخلاصة

يشهد مناخ العالم تغييرات كبيرة نتيجة للانبعاثات الهائلة من غازات الدفيئة. تؤدي هذه الانبعاثات إلى تحديات بيئية كبيرة مثل الجفاف، والملوحة، وتلوث المعادن الثقيلة وغيرها. حيث تؤثر هذه المشاكل بشكل طويل الأمد على الأمن الغذائي، لا سيما في الدول النامية. لذا لابد من تحديد طرق مستدامة بيئيًا وفعالة اقتصاديًا للتعامل مع هذه الضغوط البيئية. يتميز الفحم الحيوي بالعديد من الصفات الفريدة التي تعزز فعاليته، وتكلفته المعقولة، وتوافقه البيئي. تشمل هذه الفوائد قدرتها على تعزيز صحة التربة، وتعزيز نمو المحاصيل وإنتاجها، وتنظيم ديناميكيات العناصر الغذائية من خلال ميزاتها التي تحافظ على الحياة الميكروبية. الفحم الحيوي يحتوي على كمية كبيرة من الكربون العضوي، وغني بالعناصر الغذائية مثل النيتروجين (N) والفوسفور (P) والبوتاسيوم (K)، ويظهر درجة عالية من المسامية، ويتميز بقدرته الملحوظة على الاحتفاظ بالماء. كذلك تعمل البكتيريا الجذرية المعززة لنمو النباتات (PGPR) كعملية تطورية مشتركة ما بين النباتات والميكروبات، حيث تظهر تفاعلات متعارضة وتآزرية مع الميكروبات والتربة. لذا تؤكد هذه المراجعة على أهمية الاستخدام التآزري للفحم الحيوي وPGPR لتحسين جودة التربة والإنتاج الزراعي في كل من البيئات المثلى والقاسية، طالما أن هذه الإضافات

تعود بالنفع المتبادل. حيث يؤدي تنفيذ هذا النهج إلى تعزيز فعالية الحفاظ على الموارد، وتخفيف الضغوط الحيوية وغير الحيوية، وفي النهاية التخفيف من آثار تغير المناخ.

كلمات مفتاحية: الفحم الحيوي، البكتريا الجذرية المحفزة لنمو النبات (PGPR)، الاجهاد الحيوي، الاجهاد غير الحيوي.

Introduction

Climate change, land degradation, pollutants, and water scarcity are all global risks that have a negative impact on the economy, society, and environment. Climate change is the primary cause of several negative events that disrupt rainfall patterns, resulting in higher sea levels, more frequent droughts, increased salinity stress, altered evaporation rates, and other effects. It may also have unintended consequences, such as disease survival during floods, increased pest and parasite resilience, and reduced plant yield (67). It has a significant impact on crops because it is directly or indirectly related to both biotic and abiotic stressors. These crops face a variety of adverse conditions, including drought, high temperatures, salt, hailstorms, flooding, and other similar challenges. These worldwide stressors are significantly reducing agricultural productivity. To address them, the most effective plant production strategies employ traditional breeding procedures, biotechnology, genetic markers and transgenic approaches, and the development of resilient species, varieties, or genotypes. Nonetheless, these techniques can be complex, expensive, and time-consuming (56).

Soil modifications have been used in agroecosystems to promote plant growth and development, primarily by introducing organic and inorganic nutrients into the soil. Soil amendments are substances added to soil to make it more suitable for plant growth. As a result, researchers have looked into alternative approaches to improving crop yield and soil quality. These include compost, animal manure, sewage sludge, green manure, agricultural waste, fly ash, biochar, and plant growth-promoting rhizobacteria (PGPR) (36 and 60). Research has consistently shown that organic soil amendments offer numerous benefits and methods for improving soil quality, such as improved soil texture, increased soil fertility, long-term soil health preservation, and, most importantly, increased agricultural crop yields due to their unique properties (5 and 56).

Biochar and PGPR have recently gained popularity as organic soil amendments due to their ability to reduce the risks associated with the use of other soil amendments under both normal and stressed conditions (44). Biochar and PGPR are two environmentally friendly substitutes that can replace or augment these chemical products. Biochar is produced by pyrolysis of organic materials at high or moderate temperatures in the absence or controlled presence of oxygen (22). Beneficial microbes and organic amendments have also been used to improve microenvironmental conditions and increase crop yield and quality in agriculture, particularly rhizobacteria that promote plant growth. PGPR are beneficial microorganisms that live in soil's root zone. These rhizobacteria colonize the soil around the roots and promote plant growth (68).

In recent years, the synergistic use of biochar and PGPR has been extensively researched as a strategy for improving soil quality and increasing agricultural productivity under both optimal and stressful conditions. These studies, whether explicitly or implicitly stated, are based on the hypothesis that biochar increases nutrient availability and creates an optimal microenvironment for PGPR proliferation and activity. This interaction enables PGPR to perform their primary functions, such as phytohormone synthesis and nutrient mobilization, more efficiently and quickly for the plant (44).

Thus, the purpose of this review is to fill a knowledge gap about the simultaneous use of biochar and PGPR as biofertilizers, particularly in terms of improving soil microbial diversity and nutrient levels under environmental stress. While biochar has an immediate impact on soil and plant ecology, PGPR have a longer-term effect on soil and plant fertility. This review also identifies future research directions aimed at maximizing the synergistic potential of biochar and PGPR in promoting sustainable agricultural practices for field crops.

Biochar production:

Biochar, also known as pyrogenic black carbon (PyC), is a carbon-rich substance produced by the pyrolysis process involving the heating of biomass in the absence or limited presence of oxygen (22). Since ancient times, the discovery of *terra preta* charcoal and other carbonaceous compounds derived from burned organic elements in Amazonian soil has sparked widespread interest in their application and usage (45). Biochar has many agricultural applications, such as increasing soil organic matter and improving its physical, chemical, and biological properties. Furthermore, it has been shown to effectively mitigate climate change by reducing carbon dioxide emissions and sequestering them in soil, where they remain stable even in humid conditions. Biochar, which is naturally hydrophobic, has the potential to be used as a stand-alone material for carbon dioxide (CO_2) capture after combustion (48), thus becoming an important tool for soil management and fertility enhancement. Furthermore, its unique properties, such as a larger specific surface area, sample surface functionality, embedded minerals, groups, porous surroundings, enhanced cation exchange, robust adsorbent capacity, micronutrients, and high environmental stability, make it ideal for reducing greenhouse gas emissions and managing the environment (2).

Biochar addition has numerous benefits, including increased soil microbial activity and absorption, increased plant nutrient availability, and reduced nutrient leaching (74). Aside from these benefits, it reduces the amount of heavy metals that crops can absorb from unfavorable or poor soil. It also improves soil aeration, porosity, bulk density, infiltration rate, overall stability, water-binding capacity, hydraulic conductivity, and stability. Biochar increases microbial populations and reduces agricultural stressors like high temperatures, water scarcity, and soil salinity (48). This improves crop growth and production, boosts biological nitrogen fixation, and increases carbon sequestration. However, the results are significantly influenced by factors such as the type of biochar used, the temperature at which it is prepared, the amount of biochar applied, and the soil composition and texture (52).

Biochar is a carbon-rich material produced through pyrolysis, a thermochemical decomposition process that occurs in an oxygen-limited environment. Biochar production employs a variety of techniques, each with unique processing conditions, reaction mechanisms, and final product properties. These techniques include hydrothermal carbonization (HTC), gasification, torrefaction, flash carbonization, and microwave-assisted pyrolysis (MAP) (Fig. 1). Furthermore, pyrolysis is divided into slow, intermediate, and fast processes based on residence time (22). Each of these techniques significantly influences the physicochemical properties of biochar, including surface area, porosity, pH, and elemental composition, which in turn determine its suitability for applications such as soil amendment, carbon sequestration, and environmental remediation (2).

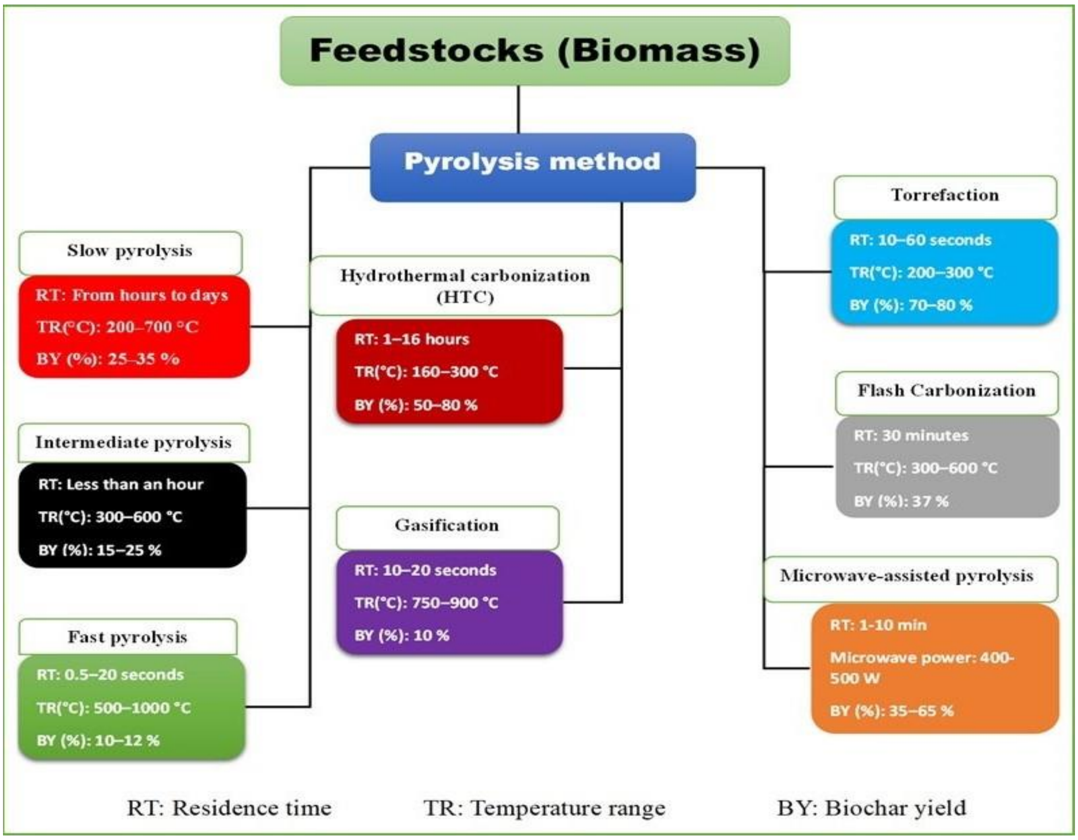

Fig. 1: Schematic representation of the temperature range, residence time, and biochar yield for different pyrolysis techniques.

1. Pyrolysis techniques based on residence time:

Pyrolysis is the most common technique for producing biochar. It involves heating biomass in an oxygen-limited or oxygen-deprived environment at temperatures ranging from 200 to 1000°C, leading to the breakdown of organic materials into biochar, bio-oil, and syngas (43). Pyrolysis is categorized into three types according to operational parameters: slow pyrolysis, intermediate pyrolysis, and fast pyrolysis, each characterized by distinct temperature ranges, residence times, and biochar yields (Fig. 1). Slow pyrolysis occurs at temperatures ranging from 200 to 700°C and residence times ranging from hours to days, resulting in a biochar yield of 25-35%. Intermediate pyrolysis produces 15-25% biochar in less than an hour at temperatures ranging from 300 to 600°C. Fast pyrolysis takes place at high temperatures (500 to 1000°C) and short residence times (0.5 to 20 seconds). This method maximizes bio-oil and syngas output while producing only 10-12% biochar. Pyrolysis technology can be implemented using a range of reactor designs, such as furnaces, rotary kiln reactors, drop-type fixed-bed reactors, vertical tube reactors, cylindrical reactors, fluidized-bed reactors, and auger reactors (58 and 59).

2. Hydrothermal carbonization:

Hydrothermal carbonization is a thermochemical process that converts biomass into carbon-rich materials in an aqueous environment at controlled temperatures and pressures, similar to natural coalification (42). Because of the high moisture content of biomass, HTC is more energy-efficient than pyrolysis because it operates at lower activation energies 150-300°C and does not require extensive drying. Hemicellulose decomposes below 250°C, cellulose around 300°C, and lignin degrades significantly above this temperature. HTC improves biochar yield efficiency when compared to pyrolysis because it allows for decomposition at lower temperatures (71).

3. Gasification:

Thermal gasification is a multi-step process that involves drying, pyrolysis, partial oxidation, and reduction. These stages occur at temperatures from 750 to 900°C and low oxygen concentrations. For practical applications, the fluidized bed reactor is preferred over other reactors due to its even temperature distribution, high heat and mass transfer rates, and other features. This process produces a syngas mixture consisting primarily of H_2, CO, CO_2, CH_4, and trace amounts of higher hydrocarbons. Gasification uses oxygen, air, steam, or a combination of the three as an oxidizer. When using air as a gasifying agent, the primary products produced are N_2, H_2, CO, CO_2, CH_4, C_2H_4, C_2H_2, and C_2H_6. The solid phase is made up of char, inorganic ash, and condensable aromatic hydrocarbons known as tars (47). Thermal gasification produces less biochar but is more stable than pyrolysis. Biomass gasification is economically feasible because it generates electricity and heat, which can be used in upstream feedstock or downstream biochar treatment processes (34).

4. Torrefaction:

Torrefaction, also known as light pyrolysis, is an alternative thermal decomposition technique. It converts biomass to biochar at temperatures ranging from 200 to 300°C in an oxygen-free environment. As a result, it can exist in both dry and wet forms. The physical and chemical properties of the resulting biochar are evaluated using the same methods as other pyrolysis processes, such as measuring the temperature at which it burns and how long it remains in the system (9). It was found (13) that raising the temperature from 245 to 300°C for 60 and 30 minutes, respectively, decreases the amount of biochar produced. Nonetheless, mild roasting at 200°C yields approximately 80% of the biochar, which stays in the system for an extended period of time. Dry torrefaction is considered as a better pre-treatment technique for fast biomass pyrolysis because it can cause significant cellulose degradation, reduce crystallinity, and promote the formation of carbonaceous residues as temperatures rise (21).

5. Flash carbonization:

Flash carbonization is a novel thermochemical technology that involves initiating and regulating rapid combustion within a densely packed bed of biomass under high pressure. This process is distinguished by a unique interaction in which the fire ascends through the biomass while air is drawn downward, allowing the transformation of lignocellulosic biomass primarily into gas and solid byproducts. Typically, the process takes less than 30 minutes, with temperatures ranging from 300 to 600°C. Flash carbonization produces biochar with an efficiency of 28 to 40%. However, a significant challenge of this technique is the need to maintain a high-pressure environment (38).

6. Microwave-assisted pyrolysis:

Microwave-assisted pyrolysis is a sophisticated thermochemical process that employs microwave power (400-500 W). This novel technique allows for short residence times (1-10 minutes) and produces biochar yields ranging from 35 to 65%, with improved heat distribution. These benefits include rapid, targeted, and energy-efficient heating, which has sparked significant scientific interest, as noted in reviews (78). MAP combines microwave radiation and traditional pyrolysis to convert electromagnetic energy into kinetic energy. Unlike conventional pyrolysis, MAP produces heat from the inside out, resulting in uniform heat distribution within the sample particles. MAP is considered a more rapid, energy-efficient, and time-effective method compared to conventional techniques, reducing production costs while enhancing biochar yield and quality (22).

Biochar's role in alleviating abiotic and biotic stress on crops:

Biochar increases crop yield under ideal conditions as well as in the presence of abiotic stressors like heavy metals, drought, salt, and high temperatures. Several studies published in recent decades have consistently reached this conclusion. For example, Hafeez et al. (30) found that the addition of biochar slightly increased the permanent wilting point while also increasing the water content at field capacity above it. This increased the amount of water available to the plants. As a result, biochar treatment may increase the soil's water-holding capacity, giving the plant easier access to water. Field trials on sandy clay soils revealed that applying 20 tons of biochar per hectare improved grain production, seedling development, and wheat, bean, and soybean germination. This improvement was attributed to a decrease in water stress (31, 48, 49).

Further, researchers found that adding biochar to inhospitable sandy soil improved water interactions between the plant, soil, and surrounding environment in both drought and irrigation conditions (33). It was also demonstrated that the use of biochar increases grain yield when water is scarce. High levels of biochar may help to reduce the negative effects of salt stress on plant growth and development (62). For example, adding 50 tons per hectare of biochar may increase bean (*Phaseolus vulgaris* L.) survival rates while lowering salt-related death rates in wheat crops. This is accomplished by reducing the negative effects of salt stress by increasing Na^+ ion absorption and K^+ ion concentration in the wood, which leads to increased production (6 and 48). Similarly, biochar made from corn stalk and rice husk enhanced rice plant growth, physiology, productivity, grain quality, osmotic stress tolerance, nutrient absorption, and soil properties. The most plausible explanation for this phenomenon is that it stimulates antioxidant enzymatic processes, increasing the activity of antioxidant enzymes such as peroxidase, ascorbate peroxidase, and catalase (32).

Recent studies have highlighted the potential of biochar in mitigating biotic stressors, such as downy mildew in crops, wheat rust, and various other plant disease systems (65 and 72). For instance, a comprehensive analysis involving 13 photosynthetic systems investigated the effects of biochar on plant diseases (48). A thorough examination of plant data revealed that 85% of the studies demonstrated positive outcomes, indicating a reduction in the severity of plant diseases with the application of biochar (12). Conversely, 3% of the studies reported adverse effects, where the addition of biochar was associated with increased disease incidence, while 12% found no significant impact (12). In a specific study by Tian et al. (65), the application of biochar derived from salt straw to tomato plants resulted in a significant reduction of bacterial wilt caused by *Ralstonia solanacearum*, with disease incidence decreasing by up to 75%.

The application of rice husk biochar increased tomato plant biomass while decreasing *Meloidogyne incognita* infection by activating defense genes like PR-1b and JERF3 (8). The use of 80 g/kg rice husk biochar significantly increased the length, surface area, and volume of apple tree seedlings. This approach mitigated the negative effects of apple replanting disease while effectively controlling *Fusarium solani* infection (70). Furthermore, several biochar studies have shown that using it at low rates and dosages effectively reduces the severity of the illness. In contrast, using high rates and doses of biochar has no effect on eradicating various plant diseases (35).

Furthermore, biochar sequesters carbon in soil via pyrolysis, converting organic carbon into stable carbon in a low-oxygen environment. This carbon can remain in the soil for hundreds or thousands of years, preventing its release into the atmosphere as CO_2 (73). As a result, biochar has an impact on rhizosphere processes by speeding up the breakdown of organic matter into minerals and facilitating the absorption of nutrients by plants. This increases plant disease resistance by reducing toxic metal availability and allowing plants to withstand biotic and abiotic stressors (49). These findings underscore the potential of biochar as a sustainable amendment for enhancing plant health and managing disease in agricultural systems.

Plant growth-promoting rhizobacteria:

Plants have long formed symbiotic relationships with various soil microorganisms, including bacteria and fungi. Plant growth-promoting rhizobacteria, a term that first appeared in 1978 (37), are associative microorganisms that live in soil, specifically in root zones near or on root surfaces. The root zone is a confined reservoir of essential nutrients, both major and micronutrients, needed for plant growth. It also has the most microbial activity when compared to other areas (68). These microorganisms affect plant growth and development, either directly or indirectly, by releasing enzymes or regulatory chemicals into the rhizosphere (67). PGPR promotes plant growth, facilitates the movement of essential nutrients, and protects plants from harmful soil pathogens. It can also reduce salt, heat, and heavy metal contamination and detect harmful substances in soil (46 and 67).

PGPR are classified as intracellular (iPGPR) and extracellular (ePGPR), in which the former is primarily found in specialized root cell nodules, whereas the latter is found in the rhizosphere and/or on the rhizoplane, or within the intercellular spaces of the root cortex. The ePGPR includes the following bacterial genera: *Agrobacterium, Arthrobacter, Azotobacter, Azospirillum, Bacillus, Burkholderia, Caulobacter,* *Chromobacterium, Erwinia, Flavobacterium, Serratia, Micrococcus,* and *Pseudomonas*. Endophytic bacteria associated with iPGPR include the *Frankia* species, which can convert atmospheric nitrogen into a form that is usable by higher plants. Other species associated with iPGPR include *Mesorhizobium, Allorhizobium, Bradyrhizobium,* and *Rhizobium* (26 and 27).

PGPR are well-known for their numerous direct and indirect plant development benefits, such as their ability to function as biofertilizers, promote root growth, resolve root issues, and manage plant stress. Although PGPR cannot completely replace fertilizers, they can help reduce the amount of chemical fertilizer needed (25). As a result, scientists studying sustainable agriculture are currently working to promote PGPR and investigate their interactions with plants. These correlations have been found in oats, canola, soybeans, potatoes, maize, peas, chickpeas, lentils, barley, wheat, radishes, and cucumbers. Furthermore, PGPR play a critical role in the soil ecosystem by performing a variety of essential functions. This makes them a valuable and sustainable resource for crop production (1, 19, 23 and 26).

PGPR colonize plant root systems and promote plant growth through a variety of mechanisms, such as solubilization of insoluble forms of P and K, fixation of N_2, synthesis of indole-3-acetic acid (IAA) and other phytohormones, production of siderophores, hydrogen cyanide (HCN), 1-amino-cyclopropane-1-carboxylate (ACC) deaminase, lytic enzymes and antibiotics (27). Certain PGPR possess distinct properties that may aid in plant development, such as the ability to detoxify heavy metals, tolerate high salt levels, withstand drought and high temperatures, and biologically manage plant diseases and insect pests (17 and 41). Thus, microbial diversity and richness vary with soil type and proximity to plant roots, crops, and tissues (10).

The role of PGPR in alleviating abiotic and biotic stress:

There are numerous strategies and techniques for reducing cellular damage caused by biotic and abiotic stressors and increasing crop tolerance, one of which is the use of PGPR. This method has received much attention because it effectively reduces abiotic and biotic stress, which has a negative impact on many aspects of natural environments such as ecology, population dynamics, ecosystem nutrient functions, plant coevolution, and horticultural plant health (25). Several studies have found that bacterial strains such as *P. putida* and *P. fluorescens* can effectively remove cadmium ions from soil and mitigate the negative effects of cadmium pollution on canola and barley crops (11). Additional research has found that PGPR improves plant tolerance to salinity and other types of biotic stress by increasing the water status of their leaves, including wheat and mung bean (4 and 50). For example, it was found (29) that ACC deaminase produced PGPR improved salt tolerance in okra by increasing the expression of reactive oxygen species pathway genes and antioxidant enzyme activity.

PGPR strains, such as *P. fluorescens* and *Arthrobacter nitroguajacolicus*, were chosen for their ability to promote plant growth and induce stress-related enzymes in rice (*Oryza sativa* L.) under various levels of drought stress (28). *P. putida* MTCC5279 also improved drought tolerance in chickpea (*Cicer arietinum* L.) plants by regulating cell membrane integrity, accumulating osmolytes like proline and glycine betaine, and effectively scavenging reactive oxygen species (66). The application of Thuricin-17, produced by *B. thuringiensis* NEB17, to water-stressed soybean plants (*Glycine max* L.) has also been shown to influence root architecture. This led to an increase in biomass, nodules, root length, abscisic acid (ABA) concentrations, and total nitrogen content (54). Pea plants inoculated with *Variovorax paradoxus* 5C-2, which produces ACC deaminase, showed increased photosynthetic rates and electron transport while maintaining balanced ion homeostasis by increasing potassium (K^+) flow to shoots and depositing sodium (Na^+) on roots. They also had lower stomatal resistance and xylem balance pressure, which resulted in higher biomass. These effects were observed under salt stress conditions with NaCl concentrations of 70 and 130 mM (69).

Studies on plant biotic stress have shown that PGPR protects plants from infection by activating their biochemical and molecular defense mechanisms. The application of PGPR mitigates biotic stress by inducing systemic resistance (ISR), priming plants to respond more effectively to potential pathogen attacks (61). For example, *Bacillus amyloliquefaciens* strain SN13 has been shown to be an effective biocontrol agent against *Rhizoctonia solani* in a variety of plant species. Plants inoculated with *B. amyloliquefaciens* produced more secondary metabolites such as gossypol and signaling molecules such as jasmonic acid, reducing *Spodoptera exigua* larvae feeding activity on cotton (76). Similarly, another study found that *Enterobacter asburiae* strain BQ9 increased tomato resistance to tomato yellow leaf curl virus. This was accomplished by activating genes that encode key defense-related and antioxidant enzymes, such as superoxide dismutase, catalase, phenylalanine ammonia-lyase, and peroxidase (40).

The addition of *Paenibacillus lentimorbus* B-30488 to soil reduced cucumber mosaic virus RNA accumulation in *Nicotiana tabacum* cv. and white burley leaves by 91%. This was associated with increased stress and disease-related gene expression, as well as increased antioxidant enzyme activity, which indicated virus resistance. After PGPR colonization, plants with improved tissue health and physiology produced more flowers and seeds (39). Similarly, *P. lentimorbus* B-30488 produces ACC deaminase, which improves tomato resistance to the southern blight disease caused by *Sclerotium rolfsii*. Plant inoculation influenced both the ethylene pathway and the activity of antioxidant enzymes. Systemic tolerance was confirmed through analysis of pathogen-related gene expression (16).

The combined effect of biochar and PGPR under environmental stress conditions:

Climate change induces abiotic and biotic stresses that reduce agricultural output, resulting in lower yields and other negative consequences. Plant infections have a significant impact on global food security, reducing crop yields by up to 15%; however, abiotic stress can reduce them by up to 70%, resulting in significant economic losses (25). Several studies have shown that combining PGPR and biochar increases plant production in response to a variety of environmental stresses (Fig. 2). The researchers reviewed a wide range of physiological variables to determine their effect on plant growth and production (44). A study found that using a combination of ACC-deaminase-producing PGPR and biochar can check the increase in ethylene levels in plants caused by drought. This amalgamation increases the survival and growth of microorganisms in the root zone and that of plant productivity compared to using only PGPR or biochar (14).

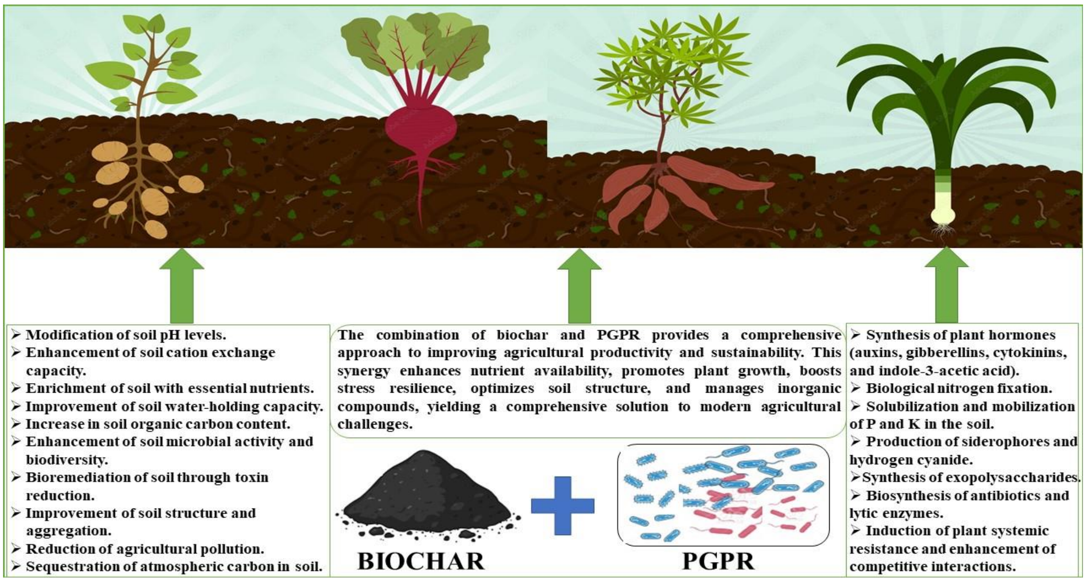

Fig. 2: The influence of biochar and plant growth-promoting rhizobacteria on plant growth and development, along with their individual and synergistic roles in alleviating biotic and abiotic stress conditions.

Several studies have found that combining PGPR (*Leclercia adecarboxylata*, *Enterobacter cloacae*, *Achromobacter xylosoxidans*, and *Pseudomonas aeruginosa*) with timber waste biochar (0.75 and 1.50%, w/w) during a drought period resulted in increased maize growth. This was accomplished by utilizing the ACC deaminase produced by these PGPR, which improved nutrient absorption while decreasing ethylene levels (15). Other studies found that combining *A. xylosoxidans* and 1.50% biochar resulted in a 19% and 6% higher transpiration rate, a 30% and 7% higher photosynthetic rate, and a 16% and 7% higher stomatal conductance compared to using them separately, especially during severe drought. The combination increased carotenoids by 28% and chlorophyll A by 13%. In addition, *P. aeruginosa* combined with biochar reduced electrolyte leakage by 28% and 4%, respectively compared to using them individually (44).

Salty soil has a significant negative impact on plant growth, development, and photosynthesis, which in turn affects protein synthesis and fat metabolism due to osmotic and hormonal abnormalities. This leads to malnutrition and stunted plant development caused by toxic ions like sodium and chloride. Only certain plants' stems contain high levels of chloride ions, which may be harmful to their health and development (55). Combining PGPR and biochar is often more effective at reducing salt stress and increasing plant production than using them separately. In a salty environment study, combining a strain of *Burkholderia phytofirmans* that produces siderophores with biochar made from tree twigs resulted in the height of the *Chenopodium quinoa* plant increasing by 17%, its dry mass of roots by 26%, its dry mass of shoots by 10%, yield growth and photosynthesis rate by 5%, and stomatal conductivity by 16% (51).

A field study was conducted to determine the effect of biochar and PGPR on salt stress mitigation in rice (*Oryza sativa* L.) grown in saline soil with an electrical conductivity of 4.67 dS/m. Biochar made from rice husk and maize stalk was combined with the PGPR strains *Bacillus coagulans* and *Pseudomonas koreensis*. In the first and second years of the experiment, the combined treatment reduced sodium (Na^+) accumulation in rice leaves by 15.34% and 15.73%, respectively, compared to the untreated control group. In addition, proline content, a common indicator of osmotic stress in plants, decreased by 49.57% and 52.49% in the first and second years, respectively (31). Another study also found that combining *Enterobacter* and *Burkholderia phytofirmans* with 5% biochar from hardwood and softwood reduced Na^+ uptake by 8% and, 25% respectively, compared to using these microbial inoculants alone (6).

Similarly, heavy metal stress in plants can be reduced by using PGPR and biochar, which can metabolize, accumulate, and eliminate toxins (46). For example, Zafar-ul-Hye et al. (75) found that adding ACC-deaminase-producing PGPR, specifically *Alcaligenes faecalis* and *B. amyloliquefaciens*, reduced lead absorption in mint leaves by 13.5%. This reduction was observed after the mint leaves were treated with compost and biochar derived from vegetable waste. As a result, the researchers found that incorporating the *A. faecalis* strain into compost-mixed biochar resulted in significantly higher nitrogen (46%), phosphorus (39%), and potassium (63%) levels, as well as in plant chlorophyll content (37%) and root dry weight (58%) compared to the control. A separate study noted that using *B. amyloliquefaciens* strains and compost-mixed biochar increased potassium absorption by 10.5% while decreasing lead uptake by 43% in spinach (74). PGPR *Enterobacter* sp. and biochar significantly improved Brassica napus growth in soil contaminated with 80 mg/kg cadmium (57).

In terms of biotic stress, biochar made from sawdust and peat moss improved the survival rates of three PGPR bacterial strains (*Bacillus pseudomycoides* M3, *Brevibacillus brevis* M4, and *Stenotrophomonas maltophilia* BG4). This was achieved by reducing disease incidence and increasing tomato output. These strains have regulatory control over their antifungal activity against *Fusarium oxysporum* F. sp. *lycopersici*, a wilt-causing fungus (18). The study also showed that adding the *Bacillus subtilis* SL-13 strain, which can control pathogenic organisms, to cotton straw biochar produced at temperatures ranging from 400 to 600 °C had a greater impact on the development of pepper growth. As a result, the microbial biochar formulations improved soil quality and texture while promoting plant growth. This significantly improved soil physical-chemical properties, enzyme activity, and pepper plant development compared to treatments containing only *B. subtilis* SL-13 or biochar (63, 64).

Conclusions

Agriculture and soil have always been essential for the sustenance of humanity on our planet. The uncontrolled use of resources has led to a gradual decrease in production, as humans constantly explore novel ways to meet their basic needs. As a result, when critical food crops are exposed to a variety of environmental stresses, they develop poorly and eventually fail to produce a harvest.

Biochar is a carbon product produced by heating biomass, such as agricultural waste, in a process known as pyrolysis. It is a valuable product that is also sustainable and environmentally friendly. Thus, due to its inherent physical, chemical, biological, and nutritional properties, biochar may help to stimulate vital and beneficial bacteria that aid in plant development. PGPR serve a variety of functions, including enhancing plant development, remediating contaminated and degraded soil, wastelands, and nutrient-rich water bodies, regulating pesticide contamination, and mitigating various environmental stressors.

Hence, this research recommended the simultaneous use of biochar and beneficial PGPR. This combination provides a long-term, sustainable, cost-effective, and environmentally friendly solution for improving crop production and soil health. These components work together to improve soil quality and plant growth efficiency, thereby reducing the need for chemical fertilizers.

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