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Enhancing Crop Resilience to Climate Change through Biochar: A Review

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Crop resilience is crucial in the face of climate change, as agricultural regions face unprecedented challenges such as rising global temperatures, altered precipitation patterns, and increased extreme weather events. These changes impact food security, crop yields, and the livelihoods of millions of farmers worldwide. Crops face threats from heat stress, changing pest and disease dynamics, water scarcity, and unpredictable growing seasons. Crop resilience involves a complex interplay of genetics, environmental factors, and agricultural practices. Researchers and agricultural scientists are exploring innovative approaches like selective breeding, genetic modification, and precision agriculture to enhance crop resilience. Integrating traditional knowledge and indigenous farming practices into modern agricultural strategies is essential for securing food production, ensuring the sustainability of agricultural systems, conserving biodiversity, and supporting community resilience in an uncertain climate future. Crop resilience is central to ensuring global food security, supporting rural livelihoods, preserving ecosystems, and advancing sustainable agriculture in the face of climate change challenges. Biochar, a climate-resilient agricultural amendment, is gaining attention for its role in enhancing agricultural sustainability and mitigating

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climate change. Its porous structure and high carbon content sequester carbon dioxide, improve soil health, and reduce nutrient leaching. Biochar's porous nature fosters a rich microbial community, aids in nutrient cycling, and aids in rehabilitating degraded soils. It also reduces synthetic fertilizer requirements and environmental pollution. Climate change significantly impacts crop agriculture, disrupting traditional growth patterns and threatening global food security. High temperatures cause heat stress, while droughts and floods cause soil desiccation, impairing crop yields. Increased plant diseases and pests spread, while higher CO2 levels stimulate photosynthesis but reduce essential nutrients. Rising temperatures disrupt vegetative and reproductive growth phases, pollination, and seed formation, compromising crop quality and market value. Biochar is a porous material formed through pyrolysis, a process where organic biomass is decomposed under limited oxygen conditions. It is primarily carbon-rich but contains hydrogen, oxygen, nitrogen, and minerals. As a soil amendment, biochar is a stable carbon sink with a high carbon content of 70-90%. Its porous structure allows it to efficiently adsorb and retain water, nutrients, and organic compounds. Its large surface area facilitates interactions with soil microbes and nutrient ions, and its high CEC helps in nutrient retention and soil fertility.

Keywords: Crop yields; disease dynamics; crop resilience; soil desiccation; carbon sink; CEC.

1. INTRODUCTION

1.1 Background and Importance of Crop Resilience in the Face of Climate Change

Crop resilience is crucial in the face of climate change, as agricultural regions are facing unprecedented challenges due to rising global temperatures, altered precipitation patterns, and increased extreme weather events [1]**.** These changes impact food security, crop yields, and the livelihoods of millions of farmers worldwide. Crops face threats from heat stress, changing pest and disease dynamics, water scarcity, and unpredictable growing seasons. Crop resilience involves a complex interplay of genetics, environmental factors, and agricultural practices [2]. Developing resilient crop varieties and implementing climate-smart agricultural techniques are essential. Researchers and agricultural scientists are exploring innovative approaches like selective breeding, genetic modification, and precision agriculture to enhance crop resilience [3]. Traditional knowledge and indigenous farming practices are being integrated into modern agricultural strategies. Enhancing crop resilience is not only about securing food production but also ensuring the sustainability of agricultural systems, conserving biodiversity, and supporting community resilience in an uncertain climate future. This underscores the importance of ongoing research, policy initiatives, and international collaborations to build resilient agricultural systems capable of withstanding climate change's challenges [4].

Crop resilience is crucial in ensuring global food security, alleviating poverty, and promoting sustainable agricultural practices [5-8]. It acts as a buffer against unpredictable climate change impacts, such as extreme weather events, shifting precipitation patterns, and pests and diseases [9]. Resilient crops have adaptive traits that enable them to withstand stressors like drought, floods, heatwaves, and pest pressures, ensuring a stable food supply and safeguarding communities from hunger and malnutrition [10]. They also maintain economic stability by providing farmers with reliable yields despite climatic uncertainties, bolstering livelihoods and rural economies [11]. Resilient crops also contribute to environmental conservation by reducing the need for excessive water and chemical inputs, promoting efficient resource utilization, and conserving soil structure and biodiversity. They also promote sustainable agricultural practices, such as conservation agriculture techniques, crop rotation, and agroforestry, leading to healthier soils, enhanced carbon sequestration, and reduced greenhouse gas emissions [12]. Thus, the pursuit of crop resilience is central to ensuring global food security, supporting rural livelihoods, preserving ecosystems, and advancing sustainable agriculture in the face of climate change challenges.

1.2 Overview of Biochar as a Climate-Resilient Agricultural Amendment

Biochar, a climate-resilient agricultural amendment, is gaining attention for its role in enhancing agricultural sustainability and mitigating climate change. Its porous structure and high carbon content not only sequester carbon dioxide but also imbue soils with remarkable properties [13]. Bio char functions as a carbon sink, capturing and storing carbon, thereby mitigating greenhouse gas emissions. It also acts as a potent soil amendment, enhancing soil structure, fertility, and water retention capacity, resulting in improved soil health, increased nutrient availability, and reduced nutrient leaching [14]. Biochar's porous nature fosters a rich microbial community, aiding in nutrient cycling and disease suppression. Its ability to retain water helps agriculture adapt to climate change-induced droughts by mitigating water stress on crops [15]. Biochar also facilitates the reduction of synthetic fertilizer requirements, minimizing nitrogen runoff and environmental pollution [16, 17]. It aids in remediating degraded soils, turning barren lands into productive agricultural spaces. Biochar represents a beacon of sustainable and environmentally conscious agriculture, combining climate change mitigation, soil fertility, and agricultural resilience.

2. CLIMATE CHANGE IMPACT ON AGRICULTURE

2.1 Effects of Climate Change on Crop Growth, Yield, and Quality

Climate change significantly impacts crop agriculture, disrupting traditional growth patterns and threatening global food security. High temperatures cause heat stress, which hinders plant physiological processes, leading to reduced crop growth rates. Droughts and floods, on the other hand, cause soil desiccation, affecting water and nutrient access, impairing crop yields [18]. Climate change also increases the prevalence and spread of plant diseases and pests, affecting yield and crop quality. Higher levels of carbon dioxide (CO2) in the atmosphere can stimulate photosynthesis, but it often leads to a decline in essential nutrients, reducing crop nutritional quality [19]. Rising temperatures disrupt the balance between vegetative and reproductive growth phases, affecting flowering, pollination, and seed formation, leading to decreased yields and compromised crop quality (Fig. 1). Altered climate conditions also disrupt the synchrony between crops and their pollinators, reducing seed production and yield. Variations in temperature and humidity also affect post-harvest storage, making crops more susceptible to spoilage, affecting their quality and market value [20].

2.2 Challenges Faced by Farmers Due to Climate Variability

Climate variability poses numerous challenges to farmers worldwide. Unpredictable precipitation patterns, such as droughts or floods, affect soil moisture levels, making it difficult for farmers to plan irrigation and impacting crop growth [21]. Rising temperatures exacerbate this issue, causing soil moisture to evaporate quickly and accelerating pest and disease growth, which jeopardizes crop yields. The frequency of extreme weather events increases, causing crop destruction and eroded topsoil, affecting long-term productivity [22]. Climate change also leads to increased pest and disease outbreaks, with warmer temperatures and altered humidity levels creating favorable conditions for pests and pathogens, leading to crop losses. Water scarcity is another critical challenge, with changing precipitation patterns often resulting in reduced water availability for irrigation. Soil degradation is exacerbated by climate variability, with intense rainfall leading to soil erosion and depletion of essential nutrients [23]. Financial instability due to crop losses is compounded by crop insurance not covering all losses, leaving farmers financially distressed. Changing climate patterns disrupt traditional farming knowledge, necessitating constant adaptation. Addressing these challenges requires a multi-faceted approach, including developing climate-resilient crop varieties, implementing sustainable water management practices, promoting soil conservation techniques, providing farmers with timely weather information and training on adaptive agricultural methods, and international cooperation and policy initiatives [24].

2.3 Need for Climate-Resilient Agricultural Practices

Climate change poses significant threats to global food production, including disrupted crop growth, droughts, and extreme weather events. Implementing climate-resilient agricultural practices ensures food security, enhancing rural livelihoods, preserving biodiversity, and mitigating greenhouse gas emissions [25]. Climate-resilient practices, such as drought-resistant crops, efficient irrigation methods, and soil conservation techniques, protect farmers' incomes and foster economic stability in rural communities. Cultivating diverse crop varieties and agroforestry promotes biodiversity, which is crucial for future crop breeding efforts. Sustainable farming methods sequester carbon

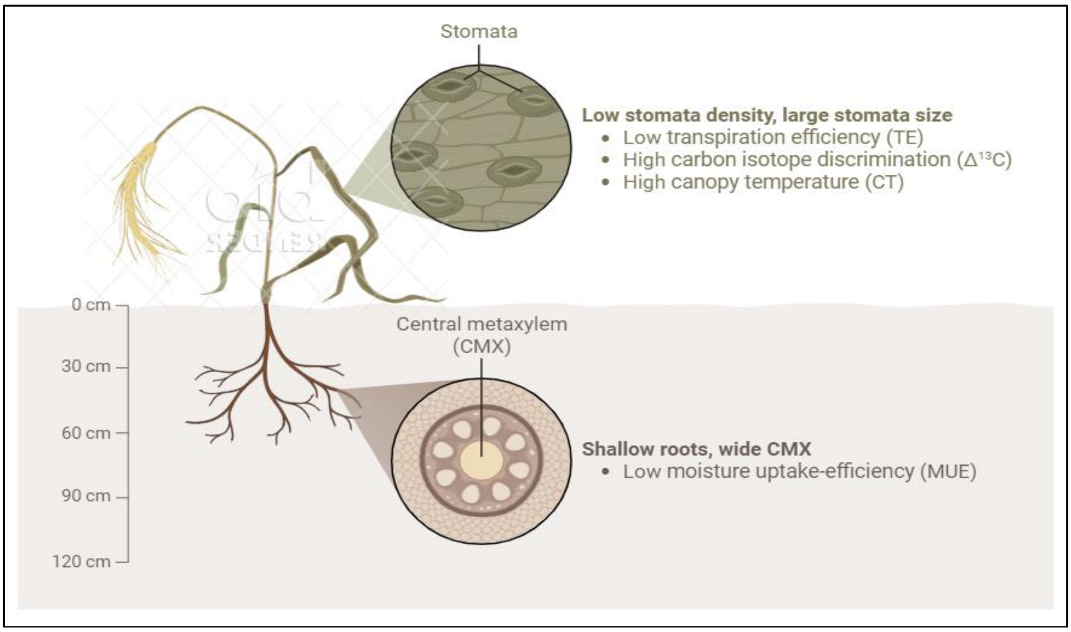

Fig. 1. Effects of climate change on crop

in the soil, reducing agriculture's carbon footprint [26]. Adapting to changing conditions, such as rainwater harvesting, intercropping, and conservation tillage, equips farmers with tools to manage changing conditions effectively. Efficient water management systems, like drip irrigation and rainwater harvesting, ensure the sustainable use of water resources, even in drought-prone regions. Climate-resilient practices prioritize environmental sustainability, conserving soil, water, and biodiversity, thereby reducing the overall environmental impact of agriculture [27].

3. BIOCHAR: COMPOSITION, PRODUCTION, AND TYPES

3.1 Composition and Properties of Biochar

Biochar is a carbon-rich, porous material formed through pyrolysis, a process where organic biomass is decomposed under limited oxygen conditions. Its composition varies based on feedstock, pyrolysis temperature, and duration [28]. Biochar is primarily carbon-rich but also contains hydrogen, oxygen, nitrogen, and minerals. The feedstock diversity, including agricultural residues and organic wastes, influences its chemical composition. During pyrolysis, volatile organic compounds are expelled, leaving a stable carbon structure [29].

Biochar, a soil amendment, is a stable carbon sink with a high carbon content of 70-90%. Its porous structure, characterized by micropores, mesopores, and macropores, allows it to efficiently adsorb and retain water, nutrients, and organic compounds [30]. Its large surface area facilitates interactions with soil microbes and nutrient ions, enhancing its efficacy as a soil amendment. Biochar's high CEC allows it to hold and exchange nutrient ions with the soil, aiding in nutrient retention and improving soil fertility. Its pH level, varying depending on feedstock and pyrolysis conditions, can neutralize acidic soils and promote plant growth. Biochar's stability ensures long-lasting effects on soil structure and fertility. It provides habitats for beneficial soil microbes, supporting soil health and nutrient cycling. Its porous structure enhances soil water retention, especially in sandy soils, aiding drought resistance in plants. Biochar's high surface area can adsorb contaminants and toxins, making it useful in environmental remediation [31].

3.2 Methods of Biochar Production: Pyrolysis, Gasification, etc

Pyrolysis is the most common method for producing biochar, which involves heating organic biomass without oxygen, resulting in the decomposition of the biomass into biochar, gases, and bio-oil. This process occurs at temperatures ranging from 350°C to 700°C and is suitable for agricultural use [32]. Gasification converts organic materials into syngas, containing hydrogen, carbon monoxide, methane, and other gases, while hydrothermal carbonization (HTC) heats wet biomass in the presence of water at moderate temperatures and elevated pressures, producing a hydrochar product like Biochar [33]. Microwave pyrolysis applies microwave radiation to organic materials, causing rapid heating and pyrolysis, offering faster processing times and being more energy efficient [34]. Flash pyrolysis involves extremely rapid heating of biomass to high temperatures within seconds, producing biochar with specific properties [35]. Torrefaction is a mild form of pyrolysis carried out at temperatures of 200°C to 300°C in the absence of oxygen, converting biomass into a more energy-dense, stable, and hydrophobic product suitable for bioenergy applications [36]. Slow pyrolysis occurs at low temperatures and longer residence times, primarily used for biochar production but also yielding higher quantities of bio-oil and gas. It is well-suited for feedstocks with high lignin content, such as wood [37].

3.3 Types of Biochar: Biomass Sources and Variability

Biochar, a versatile soil amendment, can be produced from various biomass sources, leading to diverse types. Woody biomass biochar is rich in carbon and stable, often used for improving soil structure and long-term carbon sequestration. Crop residues, such as straw, husks, and stalks, can also be converted into biochar, providing unique agricultural benefits [38]. Manure-based biochar is rich in organic matter and nutrients, aiding in nutrient retention and providing a slow-release fertilizer effect. Algae and aquatic plants biochar, like water hyacinth, are beneficial for water filtration and remediation of aquatic ecosystems due to their unique porosity and surface characteristics [39]. Nutshell biochar, produced from shells of nuts, is effective in removing heavy metals and contaminants from water. Green waste biochar, made from leaves, grass clippings, and plant prunings, is rich in nutrients and organic matter and serves as an excellent soil conditioner. Paper and cardboard biochar is used in environmental remediation and wastewater treatment, with the chemical composition and properties influenced by the ink and adhesive residues in these materials. Algal biochar, including microalgae and microalgae, is often used for carbon sequestration in marine ecosystems and agricultural soils. The nutrient content, especially nitrogen and phosphorus, varies based on algae species and growth conditions [40].

4. BIOCHAR'S ROLE IN SOIL IMPROVEMENT

4.1 Soil Structure and Nutrient Retention Enhanced by Biochar

Biochar, a carbon-rich material produced through pyrolysis, enhances soil structure by providing habitats for beneficial soil microorganisms and preventing soil compaction. Its porous structure allows for increased aeration and water infiltration, promoting better root growth and nutrient uptake by plants. Biochar's high cation exchange capacity (CEC) allows it to hold onto and exchange essential nutrients with plant roots, reducing the risk of leaching into groundwater [41]. This retention mechanism conserves nutrients and makes them more available to plants over time, promoting optimal growth. Biochar also reduces soil erosion by stabilizing soil aggregates and increasing water retention, preventing soil particles from being washed away by rainfall or irrigation. It acts as a natural pH buffer, neutralizing soil acidity or alkalinity, creating a balanced pH level for plant growth. Biochar sequesters carbon for hundreds to thousands of years, mitigating climate change and contributing to soil ecosystem health. Biochar also supports microbial activity by providing a habitat for beneficial soil microorganisms, protecting them from predation and environmental stresses (Fig. 2). This enhanced microbial activity supports nutrient cycling, decomposition of organic matter, and soil fertility [42]. Biochar's porous structure allows it to retain moisture, making it an effective tool for water conservation in agriculture. It can significantly reduce irrigation needs by retaining water and gradually releasing it to plants, especially in drought-prone regions.

4.2 Biochar's Impact on Soil Microbial Activity and Biodiversity

Biochar is a versatile material that significantly impacts soil microbial communities by providing a habitat and promoting the growth of beneficial microorganisms. Its porous structure offers protection from environmental stresses, fostering the proliferation of bacteria, fungi, and other microorganisms. This increased microbial activity supports vital soil processes like organic matter decomposition, nutrient cycling, and the conversion of organic materials into plant-available forms [43]. Biochar also promotes the growth of *mycorrhizal* fungi, which form symbiotic relationships with plant roots, facilitating nutrient uptake and enriching soil fertility. Biochar-amended soils tend to exhibit higher biodiversity due to the enhanced microbial habitat, which is essential for the breakdown of complex organic materials and ensuring nutrient availability for various plant species. Biochar's impact on soil pH and nutrient availability influences microbial communities by stabilizing pH levels and providing a source of carbon. This alters nutrient dynamics, favoring specific microbial species, leading to a diverse and dynamic soil microbiome. Biochar's antimicrobial properties, due to its high surface area and chemical composition, help suppress harmful pathogens in the soil, creating a safer environment for plants and beneficial soil microbes. Its stable carbon structure ensures its longevity in the soil, providing a continuous habitat for microbial communities and supporting long-term biodiversity. Biochar's enhanced microbial activity and carbon sequestration capacity contribute to soil resilience in the face of climate change, ensuring healthy soil ecosystems can withstand environmental stresses and improve agricultural productivity [44].

4.3 Carbon Sequestration and Soil Fertility Improvement

Biochar is a sustainable and eco-friendly alternative to traditional fertilizers. Its stable carbon structure acts as a carbon sink, sequestering carbon dioxide from the atmosphere for extended periods, reducing atmospheric carbon dioxide levels and mitigating climate change. This process also enhances soil structure by increasing porosity and stability, providing habitats for beneficial soil microorganisms and promoting aeration. This improves soil structure, preventing compaction and promoting better root growth and water infiltration. Biochar's high surface area and negative charge contribute to its high cation exchange capacity (CEC), allowing it to retain and exchange essential nutrients with plant roots, preventing nutrient leaching [45]. This retention mechanism enhances soil fertility, promoting robust plant growth and crop yield. Biochar also acts as a natural pH buffer, stabilizing soil pH levels, ensuring essential nutrients remain accessible to plants. Biochar

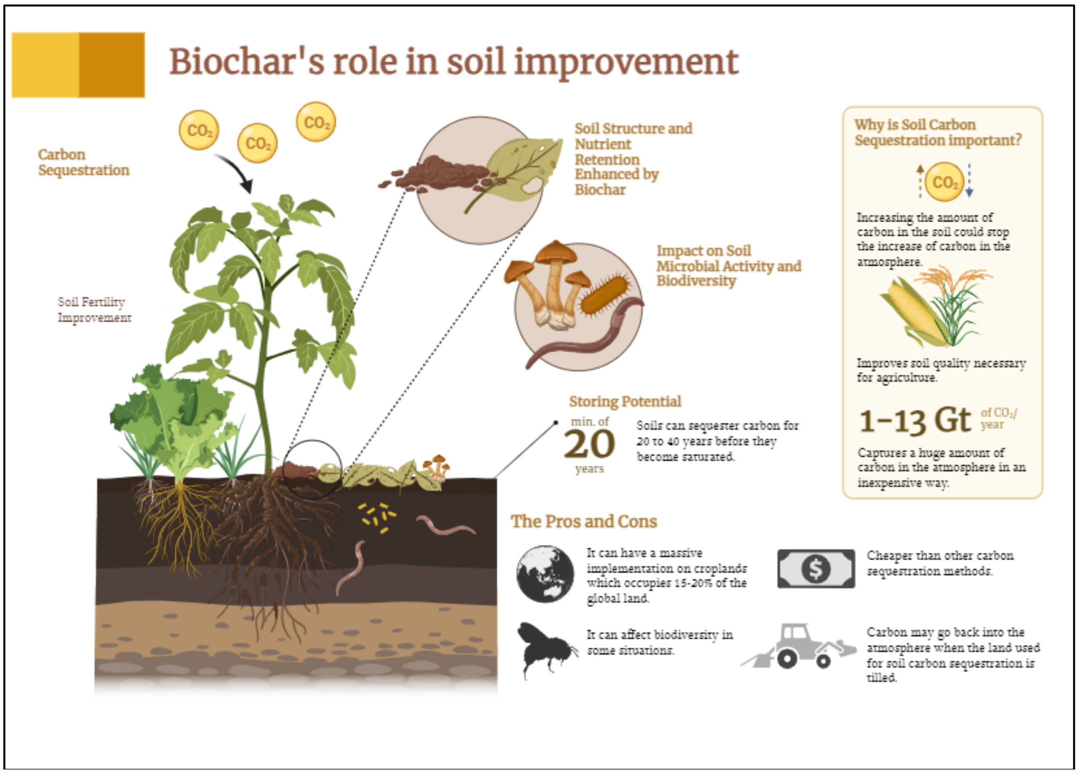

Fig. 2. Biochar's role in soil improvement

also supports microbial activity, providing a habitat for beneficial soil microorganisms, protecting them from environmental stresses and promoting their growth. This enhanced microbial activity supports organic matter decomposition, nutrient cycling, and the formation of humus, enriching the soil with organic compounds and beneficial microorganisms. Biochar also reduces greenhouse gas emissions, such as methane and nitrous oxide, by stabilizing carbon and minimizing emissions. This contributes to environmental and agricultural sustainability. Biochar-amended soils also demonstrate improved water retention capabilities, making plants more resilient to drought conditions, ensuring consistent access to water for healthy growth [46].

5. BIOCHAR AS A TOOL FOR CLIMATE-RESILIENT AGRICULTURE

5.1 Biochar's Role in Water Retention and Drought Mitigation

Biochar, a porous material, significantly improves soil's water-holding capacity by acting as a sponge, absorbing and retaining water, reducing runoff and soil erosion. It prevents soil compaction by allowing water to penetrate deeper into the soil profile, enhancing plant access to moisture. Biochar also reduces evaporation by creating a protective barrier on the soil surface, minimizing direct exposure to sunlight and wind, which accelerate water evaporation. Biochar enhances root growth by improving soil aeration and structure, promoting healthier root systems that access water from deeper soil layers. This promotes optimal plant health even in challenging conditions [47]. Biochar also retains nutrients and prevents leaching, ensuring that fertilizers and nutrients applied to the soil remain available to plants. This nutrient retention, coupled with enhanced water availability, supports plant growth even in drought-prone regions. Biochar fosters beneficial microbial communities in the soil, breaking down organic matter to create humus, which acts as a sponge, further enhancing water retention. The symbiotic relationship between microbes and plants aids in nutrient absorption, ensuring efficient water use even in water-stressed environments. By reducing water runoff and enhancing water absorption, biochar contributes to the conservation of local water resources, enabling more sustainable agricultural practices and ensuring water availability for both agricultural and environmental needs [48].

5.2 Biochar-Mediated Reduction of Greenhouse Gas Emissions

Biochar is a sustainable and environmentally friendly alternative to traditional fertilizers. Its carbon sequestration process, which locks away carbon for extended periods, helps reduce atmospheric carbon dioxide levels, a major contributor to global warming. Biochar-amended soils often show reduced methane emissions due to its porous structure, which minimizes anaerobic environments and methane-producing microbes. It also helps lower nitrous oxide emissions, a potent greenhouse gas released from nitrogen fertilizers in agricultural soils [49]. Biochar's ability to retain nutrients helps optimize fertilizer use, reducing the need for excessive fertilization. It also influences soil microbial communities and their activities, regulating certain microbial processes that can release greenhouse gases. Biochar's antimicrobial properties can suppress soil-borne pathogens, indirectly affecting greenhouse gas emissions. Biochar's positive impact on soil health, including increased organic matter and improved nutrient cycling, results in healthier, more balanced soil ecosystems [50]. Healthy soils emit fewer greenhouse gases, as they operate more efficiently. Biochar also indirectly contributes to climate change adaptation by enhancing soil fertility, promoting robust plant growth, and acting as carbon sinks for trees, which absorb atmospheric carbon dioxide, mitigating the overall greenhouse effect [51].

5.3 Biochar's Influence on Crop Tolerance to Heat and Extreme Temperatures

Biochar is a versatile material that can help plants withstand extreme heat by acting as a temperature buffer, regulating soil temperature, and preventing overheating of the root zone. Its porous structure allows it to absorb and retain moisture efficiently, ensuring a stable water supply for plants. Biochar's thermal insulating properties shield plant roots from extreme temperatures, allowing them to absorb nutrients and water more effectively. Biochar's ability to retain nutrients and prevent leaching is particularly beneficial during heat stress, as it ensures essential nutrients remain available to plants [52]. This helps plants cope with stress and enhances their tolerance to high temperatures. Biochar also promotes a healthy soil microbiome, fostering beneficial microbes that break down organic matter, creating humus, which acts as a sponge, retaining moisture and nutrients. Biochar's impact on soil structure, moisture retention, and nutrient availability reduces heat-induced oxidative stress in plants, enhancing crop tolerance to high temperatures [53].

6. CHALLENGES AND LIMITATIONS

6.1 Environmental and Ethical Concerns Related to Biochar Production and Utilization

Biochar production processes, such as pyrolysis, have a significant carbon footprint, which could offset the carbon sequestration benefits if not produced sustainably. The source of biomass for biochar production is crucial, as using agricultural residues or waste materials is sustainable but may lead to deforestation and ecosystem disruption. Incomplete combustion during pyrolysis can emit volatile organic compounds and particulate matter, contributing to air pollution. Biochar can absorb and retain heavy metals and other pollutants from the feedstock, potentially posing risks to plant and human health. Proper control measures are necessary to mitigate these emissions [54]. Biochar can also affect water resources, as runoff from biochar-amended fields may carry excess nutrients or contaminants, affecting aquatic ecosystems. Careful management practices are needed to prevent water pollution and maintain aquatic ecosystem quality. Large-scale biochar production may compete with land used for food crops or natural habitats, causing ethical concerns when it leads to land-use changes that negatively impact food security, biodiversity, or local communities' livelihoods. There are knowledge gaps regarding the long-term effects of biochar on soil, ecosystems, and human health, necessitating ongoing research to assess the true impact of biochar utilization [55].

6.2 Challenges in Large-Scale Implementation and Adoption by Farmers

Large-scale biochar production and implementation pose significant challenges, including economic viability, feedstock availability and logistics, technological standardization, market development, regulatory and policy challenges, awareness and knowledge gaps, environmental and social impact assessment, and integration with existing agricultural practices. Economic viability is crucial for small and medium-sized farmers, while feedstock availability and logistics are essential for efficient transportation and collection [56]. Technological standardization is crucial for consistent quality and effectiveness, but lack of standardized protocols and variations in production techniques hinders large-scale implementation. Market development is crucial for market growth, and educating farmers, industries, and policymakers about biochar's benefits and incentives is essential. Regulatory and policy challenges, such as permitting and certification requirements, are also crucial for facilitating the growth of the biochar industry. Awareness and knowledge gaps are barriers to large-scale implementation, and effective awareness campaigns and educational initiatives are needed to bridge these gaps [57]. Environmental and social impact assessment is vital for sustainable and responsible implementation, and integrating biochar into existing agricultural practices is challenging. Collaborations between researchers, farmers, and agricultural organizations are necessary to demonstrate the benefits and best practices for incorporating biochar into diverse farming systems.

The adoption of biochar among farmers is influenced by several factors. Firstly, increasing awareness about biochar's benefits, such as soil fertility enhancement, crop yield improvement, and climate change mitigation, is crucial. Secondly, farmers are more likely to adopt biochar when they witness tangible benefits, such as increased crop productivity, improved soil structure, and reduced fertilizer usage. Thirdly, biochar technologies and applications need to be tailored to suit local agricultural practices and environmental conditions. Lastly, participatory approaches, where farmers participate in the research and development process, foster a sense of ownership and promote adoption [58]. Lastly, capacity building is essential for farmers, as training programs teach them how to produce biochar sustainably, apply it effectively, and monitor its impact. Lastly, access to resources, such as biochar production equipment, suitable feedstock, and financial support, can encourage farmers to adopt biochar practices without significant financial burdens (Fig. 3). Lastly, peer influence, where successful biochar adopters share their experiences and outcomes, can motivate others in the community to follow suit. Lastly, policy support from governments and agricultural agencies, such as subsidies, tax benefits, or market access for biochar products, can facilitate biochar adoption [59].

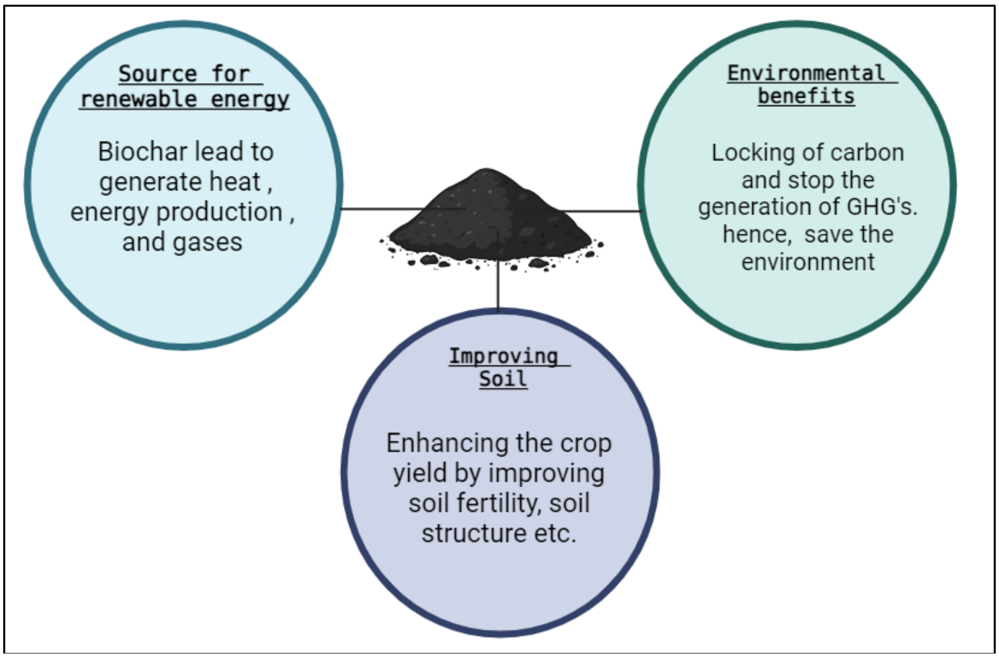

Fig. 3. Biochar helping in different fields of agriculture

7. PROSPECTS AND RESEARCH DIRECTIONS

7.1 Potential Innovations and Technologies in Biochar Production

Innovations in low-temperature pyrolysis, microwave pyrolysis, hydrothermal carbonization, gasification coupled with biochar production, continuous production systems, in-situ biochar production, integrated bioenergy and biochar systems, tailored biochar for specific applications, sensor technologies and process control, and carbon capture and utilization (CCU) are all potential methods for biochar production. Low-temperature pyrolysis reduces energy consumption and makes biochar production more cost-effective. It preserves more of the feedstock's organic matter, enhancing its nutrient content and carbon sequestration potential [60]. Microwave-assisted pyrolysis allows for rapid and efficient biochar production, resulting in a more consistent and high-quality product. Hydrothermal carbonization converts biomass into biochar in a water-based environment at moderate temperatures and pressures, utilizing various feedstocks. Integrating biochar production with biomass gasification processes maximizes energy efficiency and makes the process more sustainable. Continuous production systems allow for a steady output of biochar, enhancing efficiency and scalability [61]. In-situ biochar production converts biomass residues directly in the field, reducing transportation costs and emissions associated with moving biomass to a central production facility. Integrating biochar production with bioenergy generation processes creates synergies, utilizing waste heat for pyrolysis. Tailored biochar for specific applications, such as soil amendment, water filtration, or carbon capture, optimizes biochar properties. Implementing advanced sensor technologies and real-time process control systems ensures consistent quality and properties. Carbon capture and utilization (CCU) converts carbon dioxide captured from industrial processes or the atmosphere into stable biochar, sequestering carbon and reducing greenhouse gas emissions [62].

7.2 Areas of Future Research: Crop-Specific Studies, Long-Term Effects, etc

Biochar is a sustainable and eco-friendly alternative to traditional fossil fuels. It has been shown to have numerous benefits, including improved soil health, increased crop productivity, and reduced greenhouse gas emissions. However, its long-term effects are still being studied, as it can influence soil microbiota and ecosystem health. Biochar's effects on soil organisms, such as earthworms, *mycorrhizal* fungi, and beneficial insects, are also being explored. These interactions can help understand the ecological consequences of biochar application, affecting soil biodiversity and overall ecosystem health. Biochar's potential to mitigate climate change is also being explored, with studies assessing the net carbon balance in biochar-amended agricultural systems [63]. Waste biomass, such as agricultural residues, forestry waste, and organic municipal waste, can be used for biochar production, contributing to soil health and carbon sequestration efforts. Biochar composites are being developed for various applications, such as water filtration, environmental remediation, and construction. Understanding the mechanical, chemical, and environmental properties of these composites is crucial for their practical implementation. The social and economic impacts of biochar adoption on local communities, including changes in livelihoods, employment opportunities, and overall well-being, are also being studied. Policy frameworks, regulations, and incentives related to biochar production and utilization are also being researched, with a focus on sustainable practices [64].

7.3 Integrating Biochar with Other Climate-Resilient Agricultural Practices

The integration of biochar production with agroforestry systems, cover cropping, conservation tillage, crop rotation and diversification, organic farming practices, climate-resilient crop varieties, integrated pest management (IPM), community-based adaptation, and education and knowledge transfer are all significant ways to enhance soil health, biodiversity, and carbon sequestration. Agroforestry systems utilize organic residues for biochar production, which enhances soil structure, biodiversity, and carbon sequestration. Cover cropping, combined with biochar application, improves soil health and reduces erosion by protecting soil structure, enhancing nutrient cycling, and improving water retention. Conservation tillage methods, such as no-till farming, reduce soil disturbance and erosion by incorporating biochar into no-till systems [65]. Crop rotation and diversification strategies enhance soil fertility and resilience by providing a continuous supply of organic matter and aiding in nutrient retention. Water harvesting and management techniques optimize water use by utilizing biochar-enhanced soils, ensuring crop yield stability during dry periods. Integrating biochar into organic farming practices enhances the effectiveness of organic inputs and promotes sustainable soil fertility and resilience [66]. Climate-resilient crop varieties are planted in biochar-amended soils, ensuring access to essential nutrients and moisture even under adverse climatic conditions. Integrated pest management (IPM) practices also enhance soil health by promoting the growth of beneficial insects and microbes that act as natural pest control agents. Community-based adaptation initiatives involve engaging communities in biochar production from locally available biomass and integrating it into their agricultural systems. Education and knowledge transfer are crucial for farmers to make informed decisions about integrating biochar into their existing agricultural practices, maximizing its benefits for climate resilience [67].

8. POLICY IMPLICATIONS AND ADOPTION STRATEGIES

8.1 Government Policies Encouraging Biochar Implementation in Agriculture

Governments can provide financial incentives, research funding, tax benefits, public awareness campaigns, technical support, certification, quality standards, integration into agricultural policies, subsidies for feedstock production, and collaborative research initiatives to encourage the adoption of biochar technologies. These incentives can offset the initial costs of biochar production equipment and encourage widespread adoption. Governments can also allocate funds for research and development projects related to biochar production methods, applications, and long-term effects [68]. Tax incentives, such as reduced taxes or tax credits, can lower the tax burden on biochar-related activities, making it financially attractive for businesses and farmers. Public awareness campaigns can target farmers, policymakers, and the general public, disseminating accurate information and dispelling misconceptions about biochar. Technical support and training programs can enhance farmers' understanding of biochar production and application. Establishing certification and quality standards for biochar products ensures consistency and effectiveness, while integrating biochar into agricultural policies provides a regulatory framework. Governments can also provide subsidies for farmers to produce biomass feedstock suitable for biochar production, promoting a circular economy and sustainable feedstock management [69].

8.2 Strategies for Farmers and Agricultural Communities to Adopt Biochar Practices

The adoption of biochar can be facilitated through various strategies. These include education and awareness workshops, demonstrations and field trials, farmer-to-farmer knowledge exchange, access to resources, financial support, farmer cooperatives, technical assistance, research partnerships, policy advocacy, and monitoring and support. Education and awareness workshops can provide scientific evidence and real-life examples of successful biochar implementation [10]. Demonstrations and field trials can showcase the positive impact of biochar on crop yield and soil health, encouraging farmers to adopt biochar practices. Farmer-to-farmer knowledge exchange encourages experienced farmers to share their experiences, creating trust and relatability. Access to resources, such as biochar production technologies, raw materials, and technical expertise, can reduce barriers and make it easier for farmers to adopt biochar practices. Financial support can be offered through incentives, subsidies, or grants, easing the initial financial burden. Farmer cooperatives or community groups focused on biochar production and utilization can facilitate bulk purchasing of equipment and feedstock, reducing costs and facilitating knowledge sharing. Technical assistance can be provided through agricultural extension services, while research partnerships can be formed with local research institutions and universities to guide farmers in adopting tailored biochar practices. Policy advocacy can lead to the development of farmer-friendly regulations and financial support mechanisms. Monitoring and support can help track the progress of biochar adoption, addressing challenges faced by farmers during the implementation phase [15].

9. CONCLUSION

The integration of biochar into agricultural practices is a promising solution to the challenges posed by climate change. Biochar enhances crop resilience by enriching soil fertility, improving water retention, and increasing nutrient availability. Additionally, its carbon sequestration potential helps mitigate greenhouse gas emissions, contributing to climate change adaptation by boosting soil health and agricultural productivity. The synergy between biochar and climate-resilient agricultural practices, such as agroforestry, conservation tillage, and organic farming, further strengthens these strategies. However, successful integration of biochar into agriculture requires a concerted effort from farmers, researchers, policymakers, and the broader community. Education and awareness initiatives are crucial to disseminate knowledge about the benefits and application methods of biochar. Financial incentives and supportive policies are also essential to make biochar technologies accessible to farmers of all scales, promoting widespread adoption. In conclusion, biochar offers a multifaceted approach to enhancing crop resilience to climate change. Its ability to improve soil health, boost agricultural productivity, and sequester carbon positions it as a vital component in sustainable agricultural practices. By fostering collaboration among stakeholders and providing necessary support, the agricultural sector can effectively harness the benefits of biochar, contributing to a more resilient and sustainable food system in the face of climate change.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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