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Sustainable Agriculture in Jordan – A Review for the Potential of Biochar from Agricultural Waste for Soil and Crop Improvement

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ABSTRACT

This review aims to demonstrate how biochar, derived from agricultural wastes can improve soil physical and chemical properties, reduce greenhouse gas emissions, and contribute to increased agricultural productivity and long-term sustainability. In this review, we analyze the effects of biochar on various soil parameters, including soil bulk density, soil porosity, microbial activity, nutrient content, cation exchange capacities, pH, water holding capacity, and infiltration rates. The results highlight the practical importance of utilizing biochar to improve soil physical and chemical properties. Additionally, the results show that biochar is a practical strategy for improving the growth and yield of crops and reducing greenhouse gas emissions. It can be concluded that biochar can significantly contribute to sustainable agriculture and food security in Jordan by improving soil health, enhancing water retention, and mitigating salinity.

Keywords: agricultural waste, biochar, crop productivity, greenhouse gas emissions, soil chemical properties, soil physical properties.

INTRODUCTION

Jordan's agricultural sector faces major challenges resulting from a combination of environmental and socio-economic factors. Challenges such as soil degradation, poor fertility and increasing salinity exacerbate limited arable land and scarce water resources (Ammari et al., 2013; Gazal et al., 2023). It was reported that 90% of the land is arid or semi-arid, with substantial portions experiencing significant degradation. Desertification affects about 80% of the country's total land area, while soil salinization impacts 30-40% of irrigated lands, particularly in the Jordan Valley. Different reasons such as traditional agricultural practices and reliance on chemical fertilizers have further degraded soil quality, creating a cycle of declining yields and rising input costs (Pahalvi et al., 2021). These challenges not only reduce agricultural productivity but also threaten farmers' livelihoods and Jordan's food security. This situation highlights the critical need for sustainable and innovative agricultural practices to restore soil health, improve water management, and enhance crop productivity.

Biochar (BC), a carbon-rich product derived from the pyrolysis of agricultural organic wastes, offers a promising solution to these challenges (Zhang et al., 2021). BC has numerous benefits, including improving soil physical properties, microbial activity, crop growth, and yield, and reducing greenhouse gas emissions (GGE) in arid and semi-arid regions such as Jordan, where water and soil resources are limited (Mohawesh et al., 2021; Albalasmeh et al., 2023).

Additionally, BC contributes to climate change mitigation and reduces the ecological footprint of agriculture by sequestering carbon in the soil and reducing the need for inorganic fertilizers. Unlike conventional carbon materials like carbon black and activated carbon from coal coke, BC is made from renewable feedstock and has a simple preparation process, making it a cost-effective and environmentally friendly solution for soil remediation and nutrient management in agriculture (Burrell et al., 2016; Kavitha et al., 2018). Transforming agricultural organic waste into BC can also be a strategy for sustainable waste management.

In Jordan, the primary source of organic waste is the organic fraction of municipal solid waste, which accounts for 50–65% of the total waste generated. There is also a surplus of agricultural organic waste that can be effectively utilized as feedstock for biochar production. The main sources of feedstock from agricultural organic waste in these regions include corn stover, sorghum residues, fruit tree cuttings (e.g., branches and leaves resulting from orchard pruning of olive, date, and citrus fruit trees), seed pods and peels from processing of fruit trees, sunflower seed shells, sugar cane bagasse (the residual fibers after sugar cane juice extraction), and date palm residues, including leaves, fronds, and other by-products from date palm cultivation. These materials are typically available in significant quantities and are suitable for biochar production. Converting agricultural organic waste into biochar can be a strategic step towards sustainable waste management and improved soil quality (Van Nguyen et al., 2022). This transformation also provides a sustainable solution for managing organic waste that would otherwise contribute to environmental pollution (Lin et al., 2021). By recycling agricultural waste through composting and converting it into biochar, farmers can improve soil organic matter content, enhance soil properties, and reduce the need for synthetic inputs (Castellini et al., 2015; Kavitha et al., 2018). Despite the potential benefits, the application of BC among farmers and researchers in Jordan remains limited (Mohawesh et al., 2018; Mohawesh et al., 2021).

The purpose of this review is to evaluate the potential of biochar derived from agricultural waste, such as crop residues and forestry residues, to address pressing agricultural issues in Jordan. Through this review, we aim to identify the specific effects of biochar on key soil physical and chemical properties, the potential of biochar to enhance crop growth and yield and to assess the role of biochar in mitigating greenhouse gas emissions.

Biochar production methods

There are various methods of producing BC from agricultural organic waste. The most common method used worldwide involves thermochemical processes, such as torrefaction and pyrolysis. The first method is torrefaction, a thermochemical conversion process in which biomass is heated to moderate temperatures between 200 °C and 300 °C in an environment with limited oxygen to prevent combustion. Compared to high-temperature pyrolysis, torrefaction produces less carbonized material with unique physicochemical properties (Chen et al., 2017; Hanoğlu et al., 2019).

The second method used to produce BC is pyrolysis, which is the heat breakdown of organic material in the absence of oxygen, which can occur at various temperatures. Pyrolysis converts agricultural waste into biochar, bio-oil and synthesis gas. The process conditions, including temperature and residence time, greatly influence the properties of the resulting biochar (Khater et al., 2024). The temperature of pyrolysis to produce BC can vary significantly, mainly depending on the desired properties of the BC and the type of biomass feedstock used (Khater et al., 2024), ranging from 300 °C to 700 °C. The pyrolysis method can be divided into two temperature ranges:

- Low-temperature pyrolysis (300 °C to 500 °C): In this method, it can be produced BC yield ranges from 15% to 35% with longer residence times (up to 4 hours) range. The process yields BC with a higher content of volatile materials, which can be more reactive and have a greater nutrient content, making it potentially more beneficial for soil amendment applications (Pariyar et al., 2020). At lower temperatures (300–400 °C), biochar tends to retain more volatile compounds and has higher porosity and surface area. This type of biochar is typically more effective at improving soil water retention and providing a habitat for soil microbes;
- High-temperature pyrolysis (500 °C to 700 °C): In this method, it can be produced BC is more carbonized, with a larger surface area, lower volatile content, and higher fixed carbon content. This type of BC is more stable in soil and has a greater potential for long-term carbon sequestration. The pyrolysis temperature is a significant factor affecting the properties of the BC produced, as higher temperatures

generally result in higher carbon content and greater BC stability (Rodriguez et al., 2020; Khater et al., 2024). Biochar produced at higher temperatures (500–700 °C) has a higher carbon content and greater stability, making it more effective for carbon sequestration and reducing greenhouse gas emissions;

In Jordan, the predominant method for producing BC is slow pyrolysis at low temperatures ranging from 300 °C to 350 °C for 2 hours (Mohawesh et al., 2018). This method is preferred because it achieves higher BC yield (25–35%) compared to higher temperatures (Mohawesh et al., 2018; Albalasmeh et al., 2023). There are several reasons for choosing this method. Firstly, low-temperature pyrolysis typically results in higher biochar yields compared to higher temperatures, as less biomass is converted into gases and liquids. Additionally, biochar produced at these temperatures has a more stable carbon structure, which is beneficial for soil amendment and carbon sequestration purposes. Moreover, this method is well-suited for Jordan as it maximizes the use of available agricultural waste and produces fewer volatile by-products. Furthermore, operating at lower temperatures can be less energy-intensive, which is advantageous in arid and semi-arid regions where energy resources may be limited or costly. Therefore, slow pyrolysis at 300–350 °C in Jordan is supported by scientific literature and aligns with global best practices for biochar production, especially in resource-limited settings (Mohawesh et al., 2018; Albalasmeh et al., 2023). The specific benefits of this method include enhanced soil fertility, effective carbon sequestration, and sustainable waste management. In conclusion, the proposal for using slow pyrolysis at 300–350 °C for biochar production in Jordan is practical and advantageous. It aligns with established practices that optimize yield and resource use while addressing environmental and agricultural needs.

The BC product is primarily composed of carbon, hydrogen, oxygen, nitrogen, sulfur, and ash. Three distinct modes of pyrolysis have been identified: slow, intermediate, and fast (Panwar et al., 2019). Notably, a higher yield of biochar was observed when employing the slow pyrolysis process compared to the other methods. The BC manufacturing process can be categorized into three primary modes of operation: batch-based processes, continuous processes, and novel processes. BC production via batch processes involves three distinct methodologies: 1) earth-based and mound kilns, 2) kilns constructed from brick, concrete, and metal, and 3) retorts. Notably, the biochar yields obtained through these methods are typically low and range from 12.5% to 30% (Kammen and Lew, 2005). Despite this, the batch process remains a popular choice in rural areas due to its relatively low operational and construction costs. In contrast, continuous BC production processes have gained widespread acceptance in the commercial sector due to their ability to maximize yield, enhance energy efficiency, and produce high-quality BC. The three main methods used in continuous processing are drum-type pyrolyzers, screw-type pyrolyzers, and rotary kilns. Research has shown that these processes produce BC with a range of 25% to 35% (Duku et al., 2011). Additionally, innovative techniques like flash carbonization have been developed to quickly and efficiently convert biomass into BC. It is worth mentioning that this method has been reported to achieve maximum BC yields of 40% to 50%, with a fixed carbon content of 70% to 80% (Evans, 2008).

Properties of biochar

The properties of biochar obtained from agricultural organic waste have different pH values, elemental compositions, cation exchange capacities (CEC), stability, application and trace element compositions as shown in Table 1.

pH

Wood-based BC from trees and tree remains biochar generally exhibit similar alkaline pH levels (8–10) and high carbon content, making them ideal for carbon sequestration and soil structure improvement. This biochar is suitable for enhancing soil fertility in nutrient-rich soils (Smith et al., 2020). In contrast, poultry waste BC has a very high pH because of its high content of calcium and magnesium, and it is rich in minerals including nitrogen, phosphate, and potassium, which is crucial for enhancing soil fertility in nutrient-poor conditions (Jones and James, 2018). Corn BC and food waste BC have slightly alkaline to neutral pH values (7–9), with diverse elemental compositions that reflect their original biomass (Lee et al., 2019). Olive mill waste BC is noted for its high content of potassium and other minerals like calcium and magnesium, beneficial for potassium-deficient soils (Davis and Franklin, 2017).

Cation exchange capacity and stability

Both wood-based and tree remains BC exhibit high cation exchange capacity (CEC) and stability, contributing to long-term carbon storage and soil structure enhancement (Smith et al., 2020). Poultry manure BC has a very high CEC, which is excellent for nutrient retention but is less stable, decomposing faster (Jones and James, 2018). Corn biochar shows moderate CEC and stability, making it suitable for general soil amendments (Lee et al., 2019). Olive mill waste BC also has a high CEC and is quite stable, while food waste BC shows variable CEC and moderate stability, dependent on specific food components (Davis and Franklin, 2017).

Application and trace elements

Wood-based biochar and tree remains BC are typically low in toxic elements, making them safe for most agricultural applications unless contaminated wood is used (Smith et al., 2020). Poultry manure BC may include high levels of heavy metals like cadmium and arsenic, therefore cautious application is required to avoid soil contamination (Jones and James, 2018). Corn BC is generally safe but can carry residues of pesticides or herbicides used on the original crop (Lee et al., 2019). Olive mill waste BC can introduce phenols and other organic compounds that might be phytotoxic, while food waste BC safety varies widely with the potential for salts and heavy metals, making source verification crucial (Davis and Franklin, 2017).

Choosing the right type of biochar involves balancing benefits such as nutrient content, pH adjustment, and soil structure enhancement against potential risks from contaminants. Wood-based and tree remains BC are preferred for long-term benefits and lower risk of contaminants, ideal for enhancing soil structure and moisture retention. Manure-based and food waste BC offer high nutrient levels but require careful handling due to potential contaminants. Olive mill waste BC is particularly beneficial in potassium-deficient soils but needs careful management of its organic compound content. The selection of biochar type is a critical decision that hinges on understanding the specific properties of each BC including pH, elemental composition, cation exchange capacity, stability, and the presence of potential contaminants. While wood-based and tree remains, BC offer long-term benefits for soil structure and carbon sequestration with minimal risk of contaminants, poultry manure biochar provides immediate soil fertility benefits but with a higher risk of heavy metals. Corn BC offers a balanced option for general soil amendments, and olive mill waste biochar is uniquely suited for potassium enrichment. Although BC food waste is nutrient-rich, it requires careful consideration due to the possible presence of salts and heavy metals. Ultimately, the effective application of BC

Table 1. Properties of biochar derived from different agricultural organic wastes

Type	pH	Elemental composition	CEC	Production temperature	Surface area (m^2/g)	Stability	Application	Trace elements and toxins	References
Wood-based biochar (from trees)	Alkaline (8–10)	High in carbon, low in nitrogen	High	300–700	24–124	Very stable	Carbon sequestration, soil structure enhancemen	Low risk unless contaminated wood is used	(Smith et al., 2020, Yargicoglu et., 2015, Boraah et al., 2023)
Poultry manure biochar	Alkaline; due to very high (calcium and magnesium)	Rich in nitrogen, phosphorus and potassium	Very high	300–700	4.3–11.6	Less stable	Nutrient-poor soils, immediate nutrient availability	Cadmium and arsenic	(Jones & James, 2018, Wystalska et al., 2022)
Corn biochar	Slightly alkaline to neutral (7–9)	Good balance of carbon and nutrients	Moderate	300–600	157.11–312.30	Moderate	General soil amendments	Low, potential contamination from pesticides/herbicides	(Lee et al., 2019, Butnan et al., 2015, Adekanye et al., 2022)
Olive mill waste biochar	Alkaline (typically around 8–9)	High in potassiu, calcium, magnesium	High	300–700	100–500	High stability	Soil lacking potassiu, structure improvement	Elevated phenols, phytotoxic organic compounds	(Davis & Franklin, 2017, Manyà et al.2014, Marks et al., 2020, Aissaoui et al., 2023)
Tree/plant remains biochar	Alkaline (8–10)	Similar to wood-based but varies by part used	High	400	35–215	High	Soil structure, water retention, carbon storage	Low risk unless sourced from contaminated trees	(Pradhan et al.,2024, Dumroese et al.,2020, Bieser et al., 2019)
Food waste biochar (such as vegetables and fruit waste)	Typically, neutral to slightly alkaline (7–9)	Diverse, depends on food waste variety	High	300–500	1.5–500	Moderately stable	Nutrient enrichment, urban gardening	Variable, possible higher levels of salts and heavy metals	(Davis & Franklin, 2017, Liu et al., 2020, Lee et al., 2018)

in agriculture depends on balancing the specific needs of the soil and crops with the properties of biochar, thereby ensuring environmental safety and agricultural productivity. Table 1 shows the properties of biochar derived from different agricultural organic wastes.

Influence of biochar on the soil health and crop productivity

Effects of biochar on soil physical properties

Soil bulk density (SBD) is defined as the mass of dry soil per unit volume, including the air space and organic material within that volume and expressed in ($g \cdot cm^{-3}$) or ($Mg \cdot m^{-3}$) (Zhang et al., 2021). SBD is a crucial indicator of soil compaction, porosity, and overall soil health. It significantly impacts water infiltration, root growth, and soil aeration. Peake et al. (2014), Sun et al. (2014), and Laird et al. (2010), have demonstrated that BC improves soil structure and reduces soil compaction, leading to a decrease in SBD. Other studies by Kavitha et al. (2018) and Głąb et al. (2016) also support the finding that biochar reduces SBD. The decrease in SBD is attributed to the porous nature of BC, which creates channels for air and water movement within the soil. These channels enhance root penetration and nutrient uptake by plants, ultimately promoting better plant growth and productivity. The influence of BC on SBD is determined by its surface area and pore size distribution. BC has a larger surface area and greater microporosity is more effective in reducing soil bulk density because it creates more pathways for air and water to flow through the soil. This correlation has been demonstrated in various studies conducted by Burrell et al. (2016). When BC is added to the soil, it significantly decreases SBD and increases total porosity. The reduction in SBD due to BC depends on factors such as the type of BC, type of soil, particle size of biochar, and the rate of addition. Similar conclusions have been reached in several investigations, including those conducted by Oguntunde et al. (2008) and Qin et al. (2016).

Soil porosity (SP) is an important physical property of soil and it is the volume percentage of the void space in porous material. The porosity is determined by the arrangement and form of soil particles, as well as their compaction (Pereira et al., 2023; Söylemez, 2023). Soil compaction is a prevalent problem in agricultural soils worldwide, it is reducing crop productivity (Hagemann et al., 2017). Also, soil porosity (SP) is crucial for soil fertility, it influences other soil properties including structure, hydraulic the potential to enhance soil aggregation (Lu et al., 2020; Schlüter et al., 2020). BC addition to soil has the potential to improve SP (Murtaza et al., 2021; Kocsis et al., 2022; Singh et al., 2022). The addition of BC to soil generally helps in the improvement of soil moisture and aeration conditions. It influences the soil compaction properties and enhances soil aggregate stability which causes the improvement in soil structural formation and thus enhances SP (Guo et al., 2021; Qian et al., 2020; Şeker and Manirakiza 2020).

BC has a positive effect on sandy soils by improving SP, permeability and soil-saturated hydraulic conductivity and on clay soil by increasing the amount of macro- and mesopores (Sun and Lu, 2014). In addition, BC improves soil compaction and water conservation by improving the connection between pores, thereby increasing water and air circulation. Furthermore, BC works well on coarse or medium-textured soils and increases plant productivity by 10% and 13%, respectively (Jeffery et al., 2011). The application of BC shifts the pore size distribution of the soil towards smaller pore sizes, which promotes plant growth (Dokoohaki et al., 2017).

Influence of biochar on soil chemical properties and nutrient content

The application of biochar significantly influences soil chemical properties and nutrient content, providing numerous benefits for plant growth and soil health.

Organic matter content

BC application increases soil organic matter (SOM) content due to its stable carbon structure, which resists decomposition. Enhanced SOM improves soil structure, water retention, and nutrient availability. BC promotes the polymerization of small organic molecules via surface catalytic activity, forming SOM and adsorbing these molecules in soil macropores (Liang et al., 2010). This increased SOM positively impacts crop yields by enhancing soil porosity, and available nutrients, and reducing soil bulk density (Akhtar et al., 2014; Asai et al., 2009).

Nutrient content and availability

BC contains essential mineral nutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S). These nutrients are gradually released into the soil, enhancing soil fertility and plant nutrient uptake (Glaser et al., 2001).

BC alters N cycling by enhancing N retention and reducing leaching. It adsorbs ammonium (NH_4^+) and ammonia (NH_3), making them available for plant uptake while minimizing gaseous N losses (Guerena et al., 2013). However, its impact on nitrate (NO_3-) leaching varies, with some studies reporting reduced leaching and others observing no significant effect (Laird et al., 2010; Cheng et al., 2012). BC can increase P availability by reducing its fixation in soils, especially acidic soils. This is due to BCs ability to adsorb cations that bind phosphate, enhancing its availability for plant uptake. Also, the K, Ca and Mg in BC contribute to soil fertility by increasing the soil's exchangeable cations, improving nutrient availability (Gaskin et al., 2008).

Carbon sequestration

As a stable carbon source, biochar sequesters carbon in soil for extended periods, reducing carbon emissions. Adding biochar to temperate zone soils effectively increases soil organic carbon, making it a valuable soil amendment (Laird et al., 2017). BC addition can significantly inhibit CH_4 emissions, with Karhu et al. (2011) demonstrating a 96% reduction. However, Alho et al. (2012) found that N_2O emissions decreased only when biochar was added at rates exceeding 5 $mg \cdot ha^{-1}$, while lower rates promoted N_2O release.

Cation exchange capacity

BC increases the cation exchange capacity (CEC) of soils, enhancing their ability to retain and supply essential nutrients to plants. The presence of oxygen-containing functional groups on BCs surface (e.g., carboxyl and hydroxyl groups) contributes to higher CEC, improving nutrient retention and reducing leaching losses (Liang et al., 2006). Biochar increased CEC by 20–40% above untreated soil (Laird et al., 2010).

Soil microbial activity

BC enhances soil microbial activity by providing a conducive habitat and increasing the availability of organic carbon and nutrients. This microbial activity is crucial for nutrient cycling and soil health (Lehmann et al., 2011). BC also supports microbial diversity by providing substrates and creating microenvironments, which support resilient soil microbial communities (Dai et al., 2021).

Soil acidity reduction

BC reduces soil acidity, which improves interactions between soil nutrients and microorganisms. It neutralizes soil acidity through its carbonyls, carbonates, phosphates, and other alkaline substances (Shi et al., 2018; Huang et al., 2023). This is particularly beneficial for crop production on acidic soils, which cover approximately 40% of arable land worldwide (Sumner and Noble, 2003). BC can also reduce the toxicities of $Al^{3+,}$ Mn^{2+}, and H^+, which inhibit root growth and nutrient uptake in acidic soils (Borhannuddin Bhuyan et al., 2019; Xu et al., 2020). However, BC alkalinity can be detrimental in already alkaline soils (pH $\geq$ 7.4), potentially harming soil quality and plant production (Salem et al., 2019).

Integration with organic fertilizers

Integrating BC with organic fertilizers can positively influence soil fauna and microbial activity, especially in degraded lands (Yan et al., 2021). Customized treatments, such as a blend of compost and BC, can dramatically enhance soil properties, demonstrating the importance of tailored applications for varied soil types (Aljardah et al., 2023).

Influence of biochar on plant growth and yield

BC is being recognized as a promising soil amendment with a high potential for increasing agricultural productivity and sustainability (Kabir et al., 2023). Its application not only enhances soil qualities but also boosts fertilizer use efficiency (FUE), resulting in increased crop yields (Wang et al., 2022) and less dependency on synthetic fertilizers by minimizing nitrogen losses and enhancing CEC (Rawat et al., 2019; Oladele et al., 2019). It was reported that biochar enhances FUE and resulting in maximum yield per kilogram of fertilizer applied (Chan and Xu, 2009), and increased nutrient uptake and improved crop growth (Yeboah et al., 2009). Application of wood BC increased crop yield improvements compared to untreated soils (Mensah and Frimpong, 2018; Amanullah et al., 2022) due to BC reduces nitrogen losses through denitrification and leaching while enhancing the soil's CEC (Pereira et al., 2017). Numerous studies have demonstrated biochar's beneficial impacts on crop growth, yield, and nitrogen use efficiency (NUE), showing its potential to increase agricultural production and soil fertility. Liu et al. (2013) found that applying less than 30 $t \cdot ha^{-1}$ of BC resulted in an average 11% increase in production, with different advantages depending on crop types such as legumes (30%), vegetables (29%) and grains (8–14%). Liu et al. (2013) emphasized biochar's ability to increase agricultural yields.

Uzoma et al. (2011) found that applying BC at rates of 15 to 20 $t \cdot ha^{-1}$ significantly increased maize growth rate, yield components and water use efficiency. Major et al. (2010) found that maize yield almost tripled, while legume biomass increased by one-fifth and grass biomass nearly doubled due to biochar application. Wood BC led to significantly higher wheat yields compared to non-amended soils (Solaiman et al. 2010) due to enhance soil water retention and nutrient retention (Chan et al., 2008). In contrast, Spokas (2010) found that wood BC alone may not consistently improve crop yield. Integrating wood biochar with inorganic fertilizers led to positive outcomes (Arif et al. 2021) such as enhanced crop growth and yield and NUE. Furthermore, the combination of BC with urea has a significant and positive effect by increasing plant biomass production and increasing root yield components (Shi et al., 2020).

The combined use of BC with organic manures has been proven to slow the decomposition of these manures, resulting in a progressive release of nutrients and decreasing nutrient losses, particularly through leaching (Mensah and Frimpong, 2018). Also, BC can be combined with traditional fertilizers to enhance its retention (Nielsen et al., 2018; Khalid et al., 2019). However, other studies have discovered that combining BC with organic or mineral fertilizers has negative consequences when compared to utilizing them alone (Seehausen et al., 2017). However, the capacity for absorption of BC is highly dependent on its parameters, such as pH, surface acidity, application rate, feedstocks utilized, and pyrolysis temperature (Yao et al., 2012). BC has carboxyl, phenolic, and hydroxyl groups which can dissociate, resulting in negative charges that attract and retain positively charged ions. These functional groups and holes increase BC surface area, improving its ability to adsorb chemicals, which is important in applications such as soil remediation or improvement (Zhang et al., 2022). In addition, Chen et al. (2021) and Shi et al. (2020) they found BC reduced nitrate and total nitrogen (TN) leaching by applied BC.

Impact of biochar on greenhouse gas emissions

BC plays a crucial role in mitigating climate change by regulating greenhouse gas (GGE) emissions in soil and other environmental processes (Mona et al., 2021). Its application can modify soil properties, which in turn affects microbial biomass, community structure, and activity, resulting in changes in GGE emissions. Anthropogenic GGE, specifically the release of methane, carbon dioxide (CO_2), and nitric oxides (NO_x), contribute significantly to climate change (Mona et al., 2021). These gasses are mostly produced by the direct combustion of agricultural waste during open burning and the decomposition of organic matter above and below ground (Lehmann et al., 2006). BC reduces greenhouse gas emissions through various mechanisms as shows in Figure 1. The first mechanism is carbon sequestration (Yang et al., 2020). BC was rich in stable carbon and can absorb carbon dioxide from the atmosphere when added to soil. Due to its slow breakdown and recalcitrant nature, BC effectively retains carbon in the soil for centuries, preventing its release back into the atmosphere (Gupta et al., 2020). Another mechanism by which BC reduces emissions is its ability to improve soil fertility and structure. With its large surface area and cation exchange capacity, BC retains nutrients in the soil, increasing soil fertility. This in turn promotes increased biomass production and carbon uptake by plants (Joseph et al., 2007). Additionally, BC helps reduce emissions of nitrous oxide (N_2O), a powerful greenhouse gas, by improving soil nutrient retention. This is achieved by immobilizing nitrogen and reducing nitrification and denitrification rates, processes that typically produce N_2O in soils. Finally, BC can also reduce methane emissions from the soil by either providing a habitat for methane-consuming microorganisms or altering soil conditions to inhibit methanogenesis (Hussain et al., 2017; Lehmann et al., 2021).

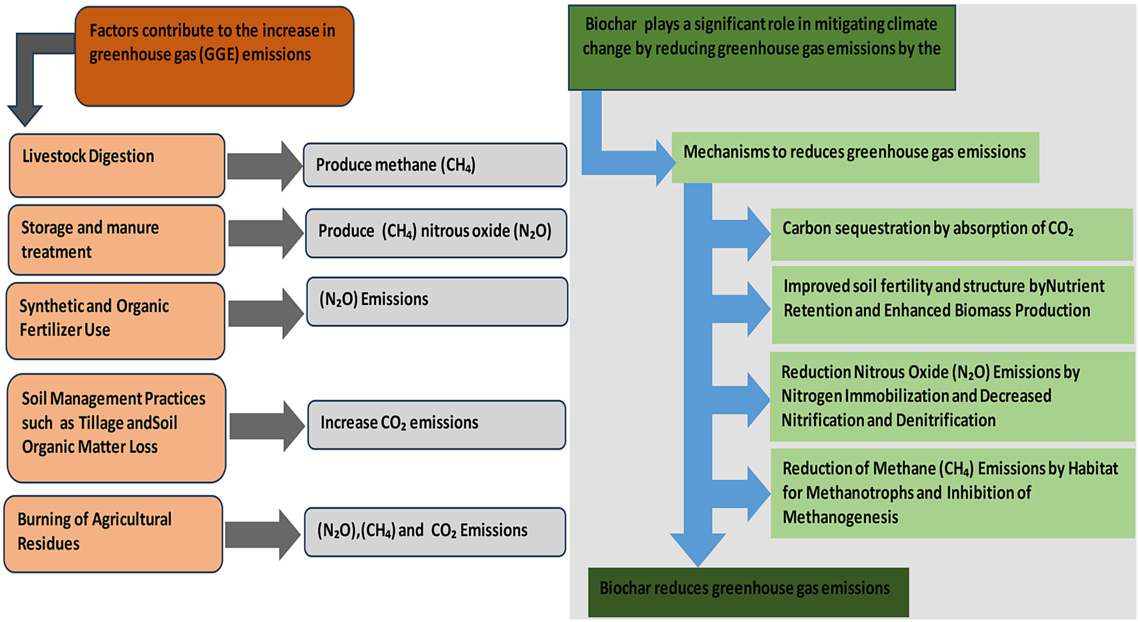

Figure 1. Mechanisms of BC to reduce greenhouse gas emissions

Challenges and limitations

Several studies have been conducted in Jordan from 2014 to 2024 (Jordan Biochar Initiative 2014; Mohawesh et al., 2018; Mohawesh et al., 2021) to assess the effects of BC on different soil types and crops, including wheat and barley. These studies consistently demonstrate that BC has positive effects, improving soil quality and increasing plant productivity significantly compared to non-BC treatments. However, despite these findings, the acceptance of BC from organic sources, such as agricultural residues, is limited among farmers, fertilizer companies, and researchers in Jordan due to various factors including: The lack of awareness among farmers, fertilizer companies, agricultural extension workers, and policymakers about the advantages of organic-derived BC, BC faces economic feasibility challenges compared to other soil amendments, such as compost. The production rate of BC from organic matter, like agricultural residuals, ranges from 25% to 35%, Also, the mechanisms for BC production in Jordan still need improvement, which hampers the optimization of production efficiency and finally, insufficient investment in BC production infrastructure and technology, leading to limited accessibility for farmers and agricultural companies. To fully harness the potential of biochar in promoting sustainable agriculture in Jordan, it is imperative for policymakers to address these barriers. This can be achieved through targeted educational initiatives to raise awareness, economic incentives to make BC more competitive, investments in advanced production technologies, and infrastructure improvements. By prioritizing these actions, Jordan can significantly improve its agricultural sustainability and productivity.

CONCLUSIONS

In conclusion, biochar derived from agricultural organic waste emerges as a highly effective and sustainable solution for addressing soil problems such as degradation, desertification and salinity. This review substantiates the pivotal role of biochar in ameliorating soil health by improving its physical, chemical, and microbial properties. Specifically, biochar reduces soil bulk density, enhances microbial activity, raises pH levels, increases water-holding capacity, and improves soil porosity and infiltration rates. These enhancements collectively create an optimal environment for plant growth, leading to increased crop yields. Furthermore, biochar significantly reduces greenhouse gas emissions and nitrogen leaching, positioning it as a viable alternative to traditional inorganic and organic nutrient sources.

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