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Application of biochar in agriculture for effective water resource conservation

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Abstract
Biochar, a carbon-rich by-product of pyrolyzed biomass, has drawn increasing interest due to its ability to enhance soil moisture retention, improve water infiltration rates, and optimize water use efficiency. However, studies on biochar application for water conservation remain limited. This article examines the potential of biochar as a sustainable water conservation measure within agricultural practices under variable climate change conditions. It reveals that biochar may offer promising avenues for sustainable water management and agricultural development through its combined effects on soil structure, nutrient retention, and microbial activity. This paper emphasizes the need for an integrated approach to water and soil management. Integrating biochar with the existing water management practices could substantially reduce irrigation demand and improve agricultural sustainability in semi-arid regions. It also provides useful recommendations for policymakers, researchers, and practitioners to prioritize future research on biochar optimization, and emphasize the development of systematic guidelines for biochar application in agriculture sector. Finally, it highlights the importance of promoting interdisciplinary collaborations to facilitate knowledge exchange and technology transfer for improved water conservation and agricultural sustainability in vulnerable water-scarce regions.

1 Introduction

Water conservation is a critical issue across the globe and is further pressured by rapid climate change [1]. Extreme weather events, such as a rise in average temperatures and fluctuation in precipitation patterns, are expected to cause serious challenges to water management and availability. Furthermore, the water cycles are shifting due to climate change, leading to prolonged droughts or frequent floods in many regions [2, 3]. All these unexpected changes intensify existing water stress, affect the ecosystem, disrupt agricultural and industrial activities, and adversely impact human health [4].

Globally, the agricultural sector consumes majority of freshwater resources, and the resilience of farming systems is compromised by reduced water availability. This impacts crop yields and exacerbates soil degradation, salinization, and desertification [5, 6]. These stresses challenge efficient water management practices that are crucial for ensuring food security and improving livelihoods. Furthermore, the race for water

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resources is intensifying among several other sectors, including industry, urban development, and precision agriculture [7]. Currently, metropolitan regions hardly meet the growing demand for drinking water due to unplanned urbanization and rapid population growth, creating inadequate sanitation and hygiene standards [8]. Water scarcity also affects aquatic ecosystems and biodiversity. The ecological balance is disturbed by declining freshwater habitats and drying wetlands, while aquatic species are threatened by decreasing river flows [9, 10].

Global water scarcity is being exacerbated by climate change, which alters precipitation patterns, increases the frequency and severity of droughts, and reduces snowpack. In water-stressed regions, these changes intensify shortages of water by disturbing hydrological cycles, affecting surface water, and further changing groundwater recharge. Reduced water availability during crucial growth seasons directly impacts agricultural productivity [11]. These effects of climate change promote selective water conservation requirements and include ecosystem-based adaptation, demand management, water recycling and reuse, and the deployment of advanced water-efficient technologies [12, 13]. Additionally, measures such as reforestation, restoration of watersheds, soil conservation, and managed aquifer recharges are valuable for enhancing water retention [14–18]. Implementing these measures is challenging under rapid urbanization and uncertain climate conditions. Furthermore, climate change poses a serious threat to both water quantity and quality, worsens existing water stress, and introduces new water management challenges. In agricultural areas, rising temperatures further worsen water deficits, reduce soil moisture content, and enhances evaporation rates [19, 20].

The water shortages have also been intensified by changes in land use and land-cover patterns due to urbanization and deforestation. These changes reduce water storage capacity and accelerate surface runoff and erosion [21, 22]. Simultaneously, climate change-induced phenomena, such as sea-level rise and saltwater intrusion damage coastal aquifers, and ultimately hamper the existing freshwater sources. This raises serious concerns for drinking water availability in communities along coastal areas [6, 23, 24]. Therefore, building resilience and ensuring reasonable access to water resources for all societal sectors is essential. This requires holistic and adaptive approaches to water resource management that integrate climate adaptation strategies. Finding technical solutions over conventional methods is especially important, particularly in developing nations.

Biochar, a carbon-rich substance obtained from the oxygen-limited pyrolysis of organic biomass, is gaining attention due to its various applications in environmental remediation, agriculture, and climate change mitigation [25, 26]. Biochar has a porous structure and high surface area and is thus considered an effective soil amendment for improving soil quality, enhancing carbon sequestration, and retaining soil moisture [26, 27]. Biochar can be used as soil amendment either on the top soil or mixed into deeper layers, with varying quantities and frequencies [28].

Several studies have demonstrated that the application of biochar can enhance carbon sequestration, reduce greenhouse gas emissions, improve soil fertility and structure, and increase crop production [29]. Some authors have also reported the role of biochar in addressing water scarcity issues in agricultural systems [28]. The capacity of biochar to enhance soil water retention and infiltration is one of the key applications for water conservation. By absorbing water through its micro-pores, biochar acts as a sponge to reduce runoff, evaporation, and water loss [30]. Both micro- and macro-pores within biochar enhance water availability for plants in sandy or degraded soils [31, 32]. This property likely mitigates plant stress, promotes efficient water use, and increases crop productivity and resilience to climate variability. Biochar enhances soil porosity and permeability, improves soil structure and aggregation, facilitates water infiltration, reduces surface runoff, minimizes soil erosion, and reduces nutrient leaching [33, 34].

Biochar also induces microbial communities and biochemical processes in soil, which can further enhance water retention and nutrient cycling and promote sustainable agricultural practices [31, 35, 36]. By stabilizing organic carbon in soil and reducing greenhouse gas emissions, biochar indirectly contributes to water conservation through carbon sequestration and climate change mitigation [26, 37]. As a result, biochar emerges as a flexible tool for improving water security, reducing climate change impact on agriculture and the environment, supporting climate-resilient irrigation, and promoting sustainable land management.

The main objective of this study is to critically evaluate the potential of biochar as a sustainable solution for minimizing water scarcity under the rapidly changing climatic condition. The study first investigates biochar's role in agriculturally dominated areas to conserve water resources effectively and economically. Then, the article highlights how the agriculture sector can use biochar synthesized using locally available biomass to reduce water requirements effectively. Further, the study assesses the environmental implications, trade-offs, and scalability of biochar applications for water conservation and climate-resilient agricultural systems across agroecosystems and geographical regions. Finally, the article discusses future research directions and associated challenges.

2 Review methodology

For this study, systematic searches were conducted in the Scopus database for journals indexed between January 2010 to October 2024. Keywords such as "biochar in agriculture, water conservation, climate change" and related terms were used to collect relevant articles. The database search was restricted to scientific research, and review articles published only in English (Fig. 1a). Repetitive articles and those published in non-Scopus journals were excluded at the preliminary stage.

Further, bibliographic analysis was conducted for the last 14 years, from 2010 to 2024 (Fig. 1b). The VOSviewer identified 50 potential interlinked keywords and is represented as a network graphs in Fig. 1b. Figures 1a and b form the basis for this study. VOSviewer correlates and quantifies potential publications to examine keyword inter-relationships as a network graph to better visualize topic co-occurrences across articles from the last 14 years. The final number for bibliographic analysis after eliminating duplicates and irrelevant articles was 50.

3 Biochar production and properties

3.1 Biochar production methods

Biochar production entails mainly organic waste pyrolysis, such as wood chips, animal dung, or crop leftovers, in a controlled environment with little to no air. Depending on the desired properties of the biochar, pyrolysis is typically carries out at temperatures between 300 °C and 800 °C, with variable heating rates and residence times [36].

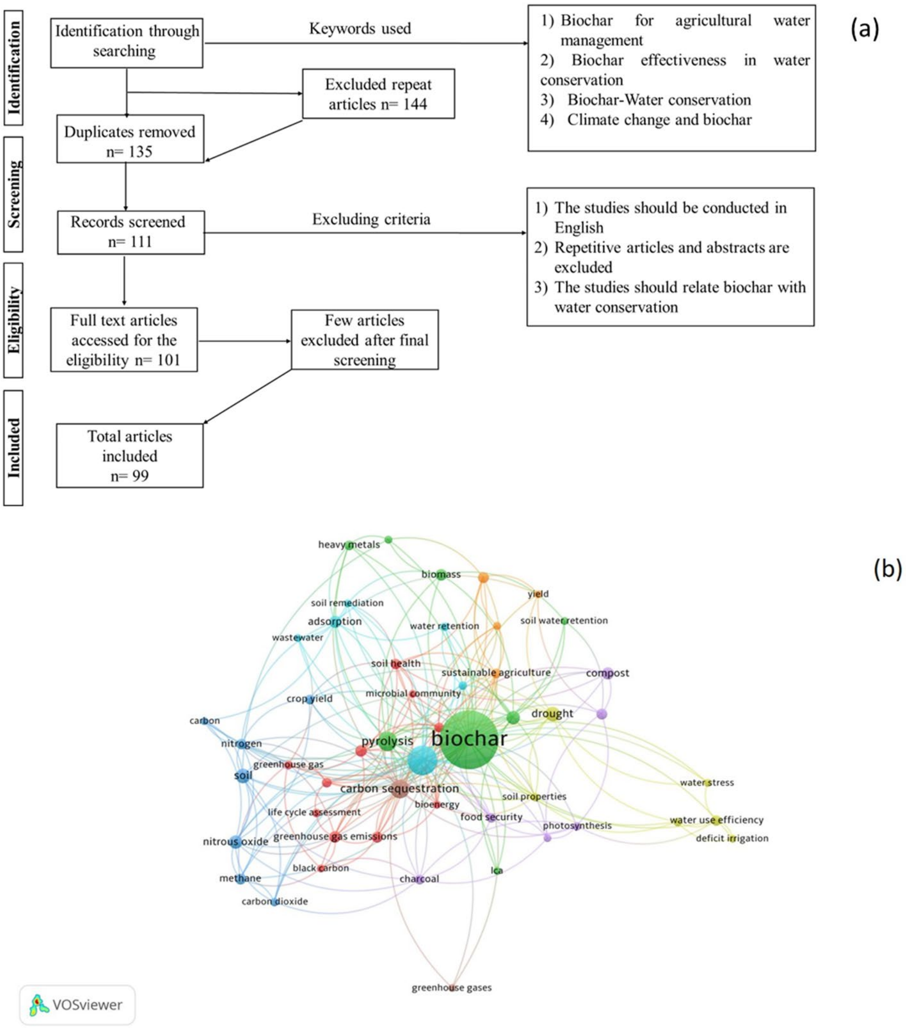

Fig. 1 **a** Framework showing methodology used for the selection of articles (**b**) Co-occurrence network of keywords, biochar, water conservation, and climate change -based on the Scopus database. Note: VOSviewer software (available at https://www.vosviewer.com/) was used for creating the bibliometric network graph

During production, the heating rate is a significant factor influencing biochar properties. Higher heating rates yield biochar with enhanced surface area, whereas lower heating rates produce biochar with greater porosity [38]. This may be because rapid heating provides insufficient time for volatile chemicals to fully escape, thereby reducing overall porosity. In contrast, slower heating rates facilitate gradual pyrolysis, allowing volatiles compounds sufficient time to escape, resulting in increased porosity and broader pore formation [39].

Many techniques are used to produce biochar such as fast pyrolysis, slow pyrolysis, gasification, torrefaction and Hydrothermal Carbonization (HTC) [29]. Slow pyrolysis involves the gradual heating of biomass to produce biochar, bio-oil, and syngas. In contrast, fast pyrolysis entails heating biomass quickly and at a higher temperature to generate a higher percentage of bio-oil. Furthermore, the gasification operations, turns biomass into a gaseous fuel (syngas) through partial oxidation [30]. HTC is the process of thermal decomposition of an organic substrate in the subcritical aqueous substrate to obtain a high carbon-containing product [25, 29]. Another thermal pre-treatment method called torrefaction is mostly used to enhance the qualities of biomass as a solid fuel. It involves heating biomass, such as wood, agricultural waste, or biological waste, to temperatures usually between 200 °C and 300 °C while maintaining an anoxic or inert environment to prevent oxygen entry. A dry, carbon-rich material known as torrefied biomass or bio-coal is the end result of this process, which also removes moisture and volatile organic components [29, 40].

During biochar synthesis, pressure also acts as a variable that modifies its properties, particularly porosity and surface area [41]. The application of high pressure in biochar production results in a more porous structure with increased surface area, i.e., high water retention in soil. The increased pressure utilized in HTC method results in a denser and more uniform biochar structure [40, 42]. Supercritical carbon dioxide (sc-CO_2) activation is an example, it is a technique for modifying biochar that utilizes pressure. The process involves exposing biochar to high-pressure carbon dioxide, which enhances its surface area and pore volume. The use of sc-CO_2 can change the chemical composition of biochar, resulting in alterations to its functional groups and adsorption properties [43]. The application of pressure during biochar production influences the types and quantities of surface functional groups on the biochar. Elevated pressure conditions can result in the formation of supplementary carboxyl and phenolic functional groups, i.e., biochar's affinity for polar contaminants as well as water retention [44]. Moreover, different production methods yield different qualities of biochar and develop unique stability, pore structure, surface area, and chemical composition, which affect the material for different uses. Biochar serves as an effective soil amendment and carbon sequestration agent due to its physical, chemical, and biological properties (Fig. 2). It further increases soil water retention, improves soil aggregation, binds labile carbon, and inhibits microbial degradation.

3.2 Properties of biochar

3.2.1 Physical properties

Biochar possesses several physical properties that are particularly relevant for retaining water and conserving soil moisture. Biochar consists of high surface area, porosity, and surface functional groups, which facilitate water retention, nutrient adsorption, and microbial habitat provision [36]. One of the key characteristics of biochar is its porous structure. The pores provide a large surface area for water adsorption and retention.

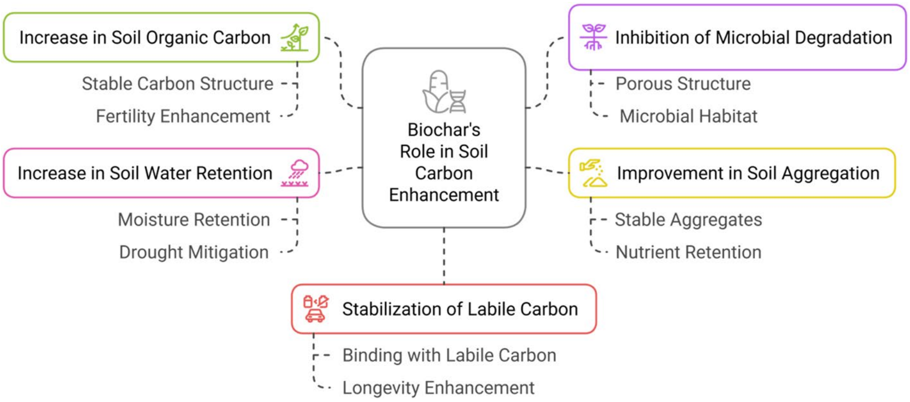

Fig. 2 Schematic representation of the role of biochar in soil organic carbon enhancement, labile carbon binding, water retention, aggregation, and microbial degradation

Biochar's micro-, meso-, and macropores create a lot of surface area and improve its ability to hold water and nutrients, which is crucial in improving the inherent properties of the soil. It creates a sponge-like matrix within the soil [28, 32]. The extensive porosity of biochar allows biochar to absorb and hold water molecules, thereby reducing water loss through drainage, and evaporation. Additionally, the porous nature of biochar facilitates water infiltration and distribution throughout the soil profile, encouraging deeper root penetration and enhances plant access to moisture [45, 46]. This property is especially beneficial in sandy or degraded soils with poor water-holding capacity, where biochar amendments can improve soil moisture retention 11.22% to 14.82% and itigate drught stress in plants [47]. Ultimately, the porous nature of biochar contributes to its effectiveness as a soil amendment tool for enhancing water retention and conservation in agricultural and environmental settings.

3.2.2 Chemical properties

Biochar exhibits several chemical properties pertinent to water retention and conservation. Chemically, the composition of biochar varies depending on the feedstock type and pyrolysis conditions but typically consists of carbon, hydrogen, oxygen, and nitrogen content [30, 48]. One crucial aspect is the presence of surface functional groups, such as hydroxyl (-OH), carboxyl (-COOH), and phenolic (-C-OH) groups, which contribute to its water retention capacity [49]. At the same time, surface functional groups, such as hydroxyl-, carboxyl-, and phenolic- groups, contribute to biochar's reactivity and ability to sorb nutrients, metals, and organic compounds from the soil environment [50–52]. These functional groups facilitate water adsorption through hydrogen bonding and other interactions, which ultimately enhance soil moisture retention [51]. Additionally, biochar's high cation exchange capacity (CEC) helps in adsorbing various potential cations, such as potassium, calcium, and magnesium, which are essential in soil structure and moisture retention [53]. By retaining these nutrients in the soil, biochar maintains optimal soil moisture levels, reduces the risk of nutrient leaching, and promotes soil fertility and plant growth [46, 54]. Furthermore, biochar's ability to modify soil pH can influence water retention, as certain soil pH ranges are conducive to optimal water-holding capacity. In a previously conducted study, biochar neutralized acidic soil and simultaneously improved the water-holding capacity by 10–20% [29]. Hence it has been observed that the chemical properties of biochar, including its surface functional groups, CEC, and pH-modifying capabilities, significantly conserve the soil moisture.

3.2.3 Biological properties

Biochar's biological properties also facilitate the soil moisture retention, primarily through its interactions with soil microorganisms. Biochar serves as both a habitat and carbon source for soil microorganisms, influencing soil microbial communities, nutrient cycling, and plant-microbe interactions [31, 55]. As a habitat and carbon source for soil microbes, biochar also enhances microbial activity, diversity in the soil, and nutrient-cycling processes [56]. Microorganisms colonize the porous structure of biochar and form biofilms and bio-aggregates that stabilize soil aggregates and improve soil structure [57]. These microbial communities play crucial roles in organic matter decomposition, nutrient mineralization, and humus formation to indirectly impact the soil water retention [58]. Furthermore, by enhancing soil aggregation and organic matter content, biochar promotes the formation of stable soil aggregates that resist compaction and erosion, thereby maintaining soil porosity and permeability for improved water infiltration and retention. Additionally, microbial degradation of organic compounds within biochar releases by-products that contribute to soil organic matter and humus formation. It further enhances soil moisture conservation and nutrient retention [59]. Overall, the biological properties of biochar facilitate synergistic interactions with soil microorganisms, leading to improvements in soil structure, nutrient cycling, and water retention, and contributing to sustainable water management in agricultural and environmental applications.

4 Traditional agriculture and its impacts on soil and water resources

Traditional irrigation practices had also caused water quality degradation, water scarcity, and obstructed water resources. For instance, extensive irrigation has led to the unsustainable extraction of groundwater and the depletion of available surface water [5]. Prominent examples include north-western India and adjacent Pakistan, where excessive water resource utilization has reduced the availability of fresh water to other users, and increased the susceptibility of ecosystems that rely on those water sources [60]. Additionally, the widespread use of chemical pesticides and fertilizers in conventional agriculture severely threatens water quality [61]. Excess nutrients from agricultural areas such as nitrogen and phosphorus, are also carried into water bodies by runoff, causing eutrophication, and toxic algal blooms [62–64]. Ultimately, these pollutants endanger both human health and aquatic ecosystems.

Some traditional agricultural methods further jeopardize the health of ecosystems and water resources, which can often provoke soil erosion [65]. The soil structure is disturbed by conventional tillage techniques which are prevalent in many developing nations [66]. They leave the soil susceptible to erosion by wind and/or water. The effects of drought and water shortages are exacerbated when productive topsoil is lost to erosion, which also reduces the soil water retention capacity. Erosion that leads to sedimentation in water bodies further decreases water storage capacity. This complicates water management in areas dependent on reservoirs for agriculture and water delivery, hindering efforts to prevent flooding [67].

The environmental effects on water resources are exacerbated by the drainage of wetlands and the conversion of natural landscapes for agriculture, leading to habitat and biodiversity loss and changes in hydrological regimes [68]. Wetlands are essential for controlling water flow, removing environmental pollutants, and providing habitat for various faunas and floras [69]. Water quality, flood control, and groundwater recharge rates are affected when these ecosystem services are disrupted by their degradation or conversion for agricultural use. Furthermore, the water shortage problem in both farming and urban regions is the loss of natural vegetation, which lowers the infiltration capacity of soils and increases surface runoff while reducing groundwater recharge [68]. This creates a need of natural soil amendment for soil nutrient and moisture preservation in water scarce regions.

5 Role of biochar in water retention and soil moisture management

In agriculture, biochar amendments improve soil fertility, water retention, and crop productivity while sequestering carbon and mitigating greenhouse gas emissions [30, 70–72]. Biochar promotes aeration, root penetration, and water infiltration by enhancing soil structure and aggregation, improving soil water retention, and reducing nutrient leaching [31, 46, 73]. Additionally, biochar amendments can increase soil pH, enhance CEC, and adsorb toxic contaminants, thereby improving soil quality and reducing environmental risks associated with soil degradation [36, 74]. These benefits highlight the potential of biochar as a sustainable soil amendment tool over traditional methods for enhancing agricultural resilience to climate change while mitigating its environmental impacts. It is possible to employ locally accessible biomass and combine biochar production with renewable energy systems for decentralized pyrolysis units for biochar production in large-scale farms. This would be more useful in water-scarce areas while lowering costs and emissions. Application-specific biochar formulations and precision farming methods can maximize their efficacy in enhancing soil moisture retention and reducing water stress across diverse agricultural environments.

5.1 Change in soil water dynamics

Biochar improves soil water retention, increases water holding capacity and reduces water loss through several physical, chemical, and biological processes (Fig. 3). As

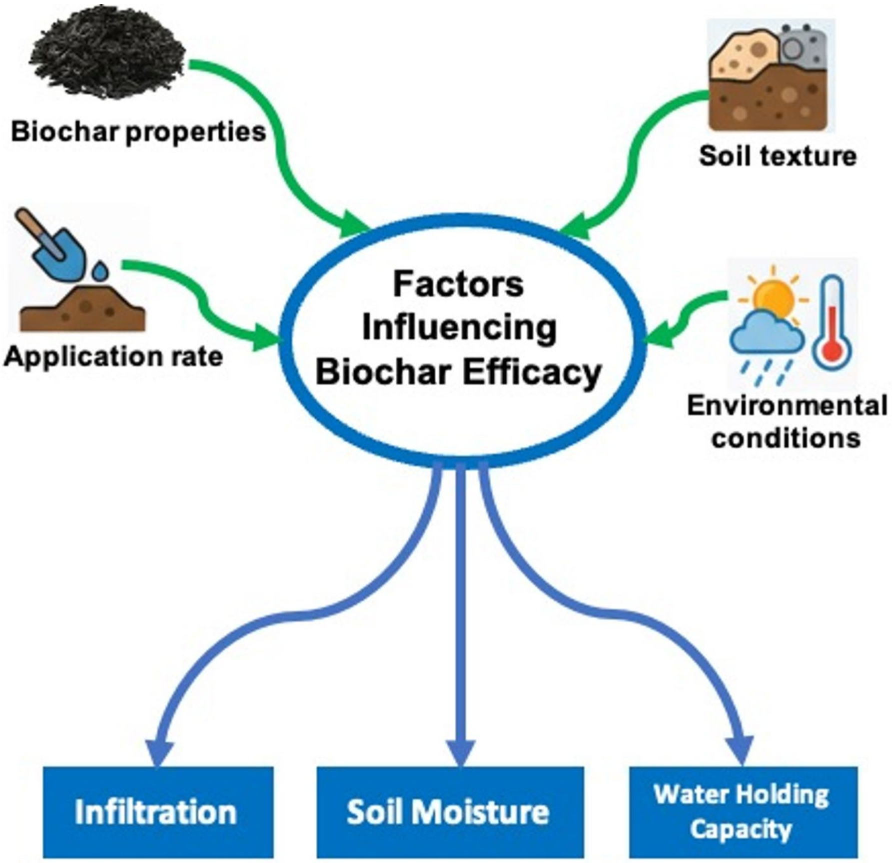

Fig. 3 Schematic representation of the factors influencing biochar efficacy on increasing infiltration, soil moisture, and water holding capacity

mentioned earlier, the porous structures of biochar improve the water-holding capacity of the soil, and form a network of micro- and macro-pores within the soil matrix [36, 75]. These fine pores serve as a reservoir for water molecules, restrict evaporation, enhance infiltration, and lower surface runoff. Biochar significantly increased the water content in the coarse-textured soils by 45%, indicating greater benefits for such soils. In the medium- and fine-textured soils, it increased the accessible water content by 21% and 14%, respectively [76]. Biochar particles also act as a binding agent, i.e., agglomerate and stabilize the soil particles against erosion [31, 57, 77]. Furthermore, biochar improves soil structure, reduces surface runoff by facilitating water penetration into deeper soil layers, and substantially enhances soil's physical qualities, preserves water resources, and lowers the risk of soil degradation [78]. Hossain et al. [27] and other researchers compiled global examples of biochar application in maintaining the pH, and increasing CEC, and organic matter [79, 80]. Biochar also significantly increases porosity and soil water content, maintains soil temperature for crop production, and controls overall bulk density [27].

Because of biochar's high porosity and ability to retain water, past studies have shown that biochar additions improve soil moisture content and alter different soil properties (Fig. 3). For instance, a meta-analysis revealed that applying biochar to soils greatly increased soil water content across various soil types and climates [30]. The sandy soils were benefited the most from biochar applications, with water retention increasing by 15–30% at 10–20 t/ha biochar application, while loamy soils showed a 10–20% improvement only [29]. Due to biochar porous nature, it forms a matrix in the soil that resembles a sponge and may absorb and hold onto water molecules. This likely minimizes the water loss through evaporation and drainage. Moreover, biochar amendments improve the organic matter content and soil aggregation, which improves plant growth and water retention [31]. Adding biochar to soil can increase infiltration rates, which enhances water moving into the soil profile and reduces surface runoff [45]. Biochar also lowers the risk of soil erosion and nutrient leaching by improving porosity and structure of the soil. This makes paths for water infiltration easier. Improved water penetration and distribution within the soil profile are indicated by the higher soil hydraulic conductivity and water infiltration rates in forest soils by biochar addition [81–83]. Hence, adding biochar to soil can improve soil permeability and decrease surface runoff, which ultimately improves the water conservation and management in environmental and agricultural contexts.

Previous researches have also shown that biochar addition to soil not only boosts its ability to retain water, and maintain soil moisture levels but also strengthens plant resistance to drought [84]. The presence of biochar in the soil create an environment conducive to water storage and availability, enabling plants to get moisture in dry weather. The soil's capability to store water and availability of nutrients is further enhanced by biochar's ability to retain nutrients and minimize nutrient leaching [29, 54]. These findings indicates that biochar has the potential to be a win-win solution for farmers involved in sustainable water management, and agricultural resilience under rapid climate change conditions.

5.2 Impact on soil erosion and runoff

Biochar's substantial contribution to reducing soil erosion and runoff supports water resource preservation and environmental sustainability. Its network of interconnected pores promotes soil aggregation and stability, reducing the soil's vulnerability to wind and water erosion.

Biochar acts as a binding agent to keep soil particles adhered to one another and prevents erosion and soil separation during heavy rainfall events [85]. Additionally, biochar improves water penetration and distribution throughout the soil profile by increasing soil hydraulic conductivity and water infiltration rates [30]. These findings suggest that adding biochar to soil can reduce erosion by improving soil stability and decreasing surface flow, thereby protecting soil integrity, and preventing the loss of priceless topsoil. Biochar develops solid soil aggregates that withstand compaction and erosion. Additionally, Biochar amendments stimulate microbial activity and promote the production of biofilms and bio-aggregates, hence stabilizing soil aggregates and enhancing soil structure [31]. There is a lower chance of soil loss and deterioration since these stable soil aggregates are less likely to be eroded by wind and water. Furthermore, biochar raises its organic matter content in soil, which promotes soil stability and aggregation. Biochar amendments increase the organic matter content in the soil and develop stable soil aggregates, which decrease soil erosion and improve soil quality [50]. These results demonstrate how biochar supplements can protect soil integrity, reduce erosion, conserve water resources, and advance sustainable land management practices.

Nutrient runoff from agricultural fields is a major cause of eutrophication and water pollution, which harms human health and aquatic ecosystems. Studies have also shown that biochar absorbs excess nutrients from the soil environment, such as phosphorus and nitrogen, and minimizes pollution and nutrient runoff in agriculture [86]. Adding biochar to the soil creates a matrix resembling a sponge that absorbs and retains nutrients, preventing them from seeping into surface and groundwater sources. The danger of nutrient runoff and pollution could be lowered by applying biochar to soils, which enhances nutrient retention and decreases nutrient leaching [30, 54]. Furthermore, cations that are vital to soil fertility and nutrient availability, such as potassium, calcium, and magnesium, can be adsorbed by biochar due to its high CEC [50, 74]. Biochar additives improve soil fertility and nutrient cycling by holding onto nutrients in the soil, hence lowering the likelihood of pollution and nutrient runoff. Consequently, biochar can reduce soil erosion, encourage soil aggregation, and lower nutrient discharge, making it a valuable tool for protecting surface and groundwater resources.

5.3 Improvement of soil by increasing nutrient availability

An overall increase in nutrient availability has also been observed in soil after the application of biochar. Previous studies have shown that the total nitrogen of soil substantially increases after biochar addition. For instance, Gonzaga et al. [87], Yue et al. [88] and Brantley et al. [89] proved how biochar shows good results by increasing the total nitrogen of soil. Moreover, biochar also has huge potential to remove contaminants from the soils [29].

Biochar interactions with organic matter and soil microorganisms affect soil microbial activity and nutrient cycling, which indirectly affect soil water dynamics. Biochar in the soil provides an environment beneficial to soil microbes, and imperative for nutrient cycling, soil aggregation, and the breakdown of organic matter [90]. It supports the growth and activity of advantageous soil microorganisms by giving them a home and carbon sources [26, 91]. These microorganisms not only impact soil water retention but also positively affects plant growth through their activities in nutrient cycling, organic matter breakdown, and soil aggregation. As an illustration, biochar addition enhances the breakdown of soil organic matter and releases organic chemicals that improve soil structure and water retention [31]. Biochar changes the pH and nutrient availability of the soil, which can affect the plant's transpiration and water adsorption [50]. Overall, these biological interactions in soils treated with biochar improve soil water retention and reduce water loss through linked chemical, biological, and physical mechanisms. Furthermore, sustainable land management techniques can be developed to improve soil fertility, encourage water conservation, and lessen the effects of climate change on agricultural productivity and ecosystem resilience.

5.4 Biochar effects on plant-water relations

Research on the effects of biochar on transpiration rates, plant water intake, and water usage efficiency has provided valuable insights into the potential advantages of biochar additions for boosting plant-water relations and enhancing agricultural productivity. These effects depend on three major factors; biochar production, application method, and site specific conditions (Fig. 4). The addition of biochar to soil has improved water retention and increased the soil water content, which raised plant transpiration rates and water absorption [76]. Furthermore, adding biochar to the soil improves its aggregation and structure, which improves root penetration and soil moisture uptake. These results imply that charcoal/biochar amendments can enhance plant water uptake and transpiration rates by increasing soil moisture availability and root water absorption capacity.

Biochar can improve the efficiency of plants in using water, leading to higher crop yields and better utilization of available resources. Because biochar increases soil water availability and retention, plants can use water effectively and become more resilient to drought and water stress. Studies have shown that biochar addition improves water usage efficiency in drought-stricken maize crops, resulting in higher biomass production and grain yields [92, 93]. Furthermore, plant growth and development can also be optimized in biochar-amended soils due to improved water retention and nutrient availability, which eventually enhances agricultural productivity and water use efficiency. These

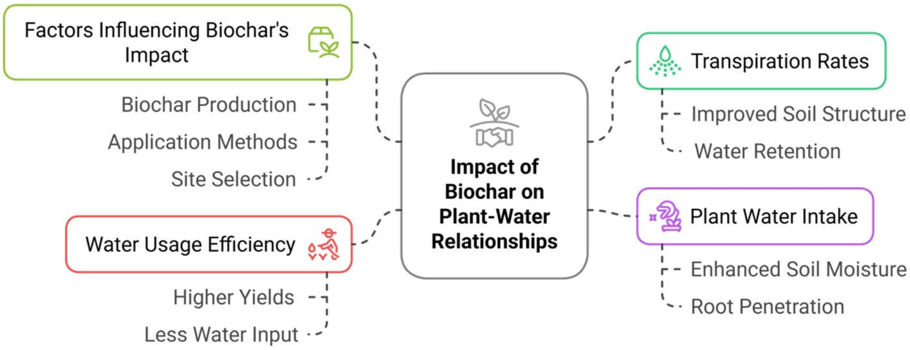

Fig. 4 Demonstration of biochar impacts on water usages efficiency of plants, transpiration rates, and plant-water uptake

results demonstrate how biochar amendments can strengthen agricultural resilience to climate variability and sustainability by optimizing water use.

Stomatal conductance and photosynthesis are two physiological processes linked to water intake and transpiration in plants. These processes are likely impacted by biochar additions. They indicate improved plant water intake and usage and, enhance the physiological properties following biochar incorporation into soils [30, 94]. The impacts of biochar on soil properties, such as improved soil structure, nutrient availability, and microbial activity, may contribute to these physiological changes. These features improve the plant-water relations and overall water usage efficiency. Therefore, the effects of biochar on plant water uptake, transpiration rates, and water use efficiency suggest that biochar amendments can improve agricultural sustainability and resilience under water stress conditions.

5.4.1 Biochar amendments on crop yield and resilience to drought stress

Biochar additions significantly impact crop productivity, and drought stress tolerance and provide viable options for water-constrained sustainable agriculture. Biochar enables soil to retain and release nutrients more effectively, providing plants a consistent supply of essential nutrients. Furthermore, biochar's capacity to enhance soil aggregation and structure encourages greater root penetration and nutrient access, which further enhances plant growth and development [75]. These results imply that biochar amendments can optimize soil fertility and nutrient availability, which can significantly improve crop production and increase agricultural productivity and overall food security.

Furthermore, biochar enhances plant resilience to drought stress and mitigates the negative impacts of water scarcity on plant growth and yield. Biochar amendments enhance crop water use efficiency, and soil water retention as well as strengthen drought resistance and resilience [30, 93]. During periods of water stress, the porous structure of biochar generates a reservoir for water storage inside the soil, giving plant roots a steady supply of moisture. These results demonstrate, how biochar application can increase crop resistance to drought stress and reduce the negative effects of climate variability on agricultural productivity.

The physiological activities of plants, includes photosynthesis, antioxidant activity, and stomatal conductance. They are linked to drought tolerance and impacted by biochar addition. The application of biochar to soils alters the physiological responses of plants, leading to improvements in drought tolerance and stress resilience. These changes include higher stomatal conductance, photosynthetic rates, and antioxidant enzyme activity [76, 95] i.e., impacts of biochar on soil characteristics, such as increased nutrient availability, soil water retention, and microbial activity. They might improve plant-water relations, and overall drought stress resilience, contributing to these physiological changes.

5.4.2 Biochar for saline water

Biochar can improve soil properties, and alleviate salt stress to reduce the negative impacts of saline water on crop productivity [84]. In an estimate, over one billion hectares of land are affected by salinity, which generates a negative effect on crop yield and growth, particularly in arid and semi-arid areas [96]. Due to its capacity to improve soil structure, increase nutrient availability, and decrease sodium toxicity in salt-affected soils, biochar has drawn great attention as a means of providing improved plant growth and yield in saline soil environment. Additionally, adding biochar to soil can improve nitrogen utilization efficiency, raise the concentrations of K^+, Ca^{2+}, and Mg^{2+}, and increase phosphorus availability by developing the growth of soil bacteria for phosphorus solubilization [54]. Biochar has a high CEC, which can adsorb and retain Na^+ and Cl^-, minimize ion toxicity, and lower their availability to plants. Furthermore, biochar encourages the formation of salt-tolerant plant and growth-promoting rhizobacteria to overcome the salinity stress [58]. By facilitating nutrient uptake and producing phytohormones, these bacteria enhance the general health of plants. Few studies have demonstrated the potential of biochar as a technique for reducing salt stress in agriculture [58]. For example, biochar enhanced the growth and yield of wheat watered with saline water [96, 97] and showed comparable benefits for tomato plants [98].

6 Environmental implications and trade-offs

There are many potential environmental advantages associated with the widespread use of biochar for water conservation. One of the key benefits of biochar application is the improvement in soil moisture retention, which helps in reducing the effect of drought and water scarcity. Water utilization in agricultural systems can more efficiently be achieved by adding biochar amendments, which can improve water infiltration rates, and increase soil water holding capacity [30, 93]. By reducing water runoff and increasing soil water availability, biochar maintains soil moisture levels, encourages plant development, and increases ecosystem resilience to climatic variability. Furthermore, biochar's capacity to enhance soil aggregation, and structure can lessen nutrient runoff and soil erosion, enhance water quality, and promote environmental sustainability.

There might also be negative effects from the extensive use of biochar, especially regarding the long-term impact on the environment and the carbon cycle dynamics. Biochar is a stable form of carbon that can be sequestered and used to reduce greenhouse gas emissions since it can linger in soils for extended periods [50]. This is still a concern regarding the durability and stability of biochar carbon storage in soils and its possible interactions with soil microbial populations and nutrient cycling mechanisms. Even though this could provide a viable solution for climate change mitigation. Furthermore, energy and carbon costs associated with biochar production and application may arise, particularly if large-scale biomass feedstocks are used, or inefficient production techniques are applied. To ensure that the environmental benefits of biochar production and use outweigh any potential disadvantages, it is crucial to analyse the life cycle consequences of these processes thoroughly.

To minimize potential hazards of biochar application to soil fertility, biodiversity, and ecosystem functioning, it is crucial to consider the selection of biochar feedstock, production methods, and application rates [31, 85]. It is important to carefully assess and monitor the use of biochar in various contexts since different feedstocks or production techniques might produce biochar with variable characteristics and environmental implications. One such concern could be the use of contaminated feedstocks that may introduce heavy metals such as cadmium, lead, or arsenic into soils, posing risks to plants and food chains [99]. Furthermore, additional investigation is required to understand the long-term impacts of biochar on soil microbial communities, dynamics of nutrient cycling, and greenhouse gas emissions. This can guarantee the sustainable and ethical deployment of biochar for environmental management and water conservation in agriculture.

Notwithstanding these advantages, a number of environmental trade-offs need to be taken into account. One such example is the use of invasive species or crop wastes, but harvesting forest biomass for energy might have negative effects on biodiversity and land-use change [100]. Furthermore, energy used in the pyrolysis process, if not adequately managed, it may emit polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), or other dangerous by-products [44]. Moreover, overuse or misaligned biochar applications can change the pH of the soil negatively or immobilize nutrients, potentially reducing crop yields [101]. Although biochar generally has a net positive environmental impact, life cycle evaluations (LCA) have revealed that these advantages differ greatly depending on the type of feedstock, the circumstances of pyrolysis, and the end-use applications [100]. Therefore, to maximize environmental benefits without unforeseen ecological effects, a sustainable biochar approach must carefully analyze the entire value chain, from feedstock selection and processing to site-specific soil and climate conditions [102, 103]. It is also imperative to critically evaluate the possible drawbacks of using biochar for environmental management, including but not limited to its effects on soil and ecosystem health, energy and emissions costs, and carbon cycle dynamics. Further research and monitoring are necessary to fully understand the long-term environmental effects of applying biochar and to guide decision-making regarding its widespread use as a water conservation tactic.

6.1 Carbon sequestration, nutrient leaching, and interactions with soil microbiota

Important questions about the dynamics of carbon sequestration, nutrient leaching, and interactions with soil microbes arise when using biochar for water conservation. Biochar is a stable form of carbon that can persist in the soil for long periods, potentially storing carbon and reducing greenhouse gas emissions [50]. However, several variables, such as the type of feedstock, production method, and the characteristics of the soil longevity and stability of biochar carbon storage in soils.

Nitrogen cycling and nutrient leaching in soils may also be impacted by biochar amendments, which in turn affect water quality and soil fertility. Biochar-containing amendments likely improve plant growth and productivity by increasing the nutrient availability and retention in the soil [30, 93]. Furthermore, high CEC and adsorption capability of biochar also retain nutrients in the soil, lower the possibility of runoff, and reduce the nutrient leaching [74]. However, there are worries, especially in soils deficient in nutrients, that excessive nutrient retention by biochar may lead to nutrient immobilization and decreased nutrient availability to plants. Thus, factors such as properties of the biochar, soil characteristics, and land management practices determine the extent to which biochar additions affect the dynamics of nutrient leaching and the water quality [31].

Biochar amendments also affect soil health, nutrient cycling, and ecosystem functioning by influencing the microbiota and microbial activity of the soil. Biochar can shape the structure and activity of microbial communities by providing habitat and a carbon source for soil bacteria [31]. Its amendments can improve soil nutrient cycle mechanisms, increase microbial diversity and abundance, and stimulate beneficial microbial activity [50, 85]. Biochar could also change the way ecosystem's function and microbial

Table 1 Effects of biochar application on soil moisture retention and water use efficiency across diverse environmental contexts globally

Region	Application	Soil type	Crops	Findings	References
India	Smallholder farming	Sandy and degraded soils	Wheat, rice	Improved soil moisture retention, increased crop yield	[107]
China	Paddy fields	Saline soils	Rice	Enhanced water holding capacity, reduced soil salinity, improved yield	[73, 108]
Australia	Dryland farming	Sandy soils	Wheat, barley	Increased soil water retention, improved drought resilience	[109, 110]
United States	Irrigated agriculture	Loam and clay soils	Maize, soybeans	Improved soil structure, increased water use efficiency	[111, 112]
Brazil	Agroforestry systems	Oxisols (highly weathered soils)	Maize, beans	Enhanced soil moisture retention, improved crop productivity	[113, 114]
Sub-Saharan Africa	Subsistence farming	Degraded soils	Maize, sorghum	Increased water holding capacity, improved food security	[92, 115]
Southeast Asia	Plantation crops	Acidic soils	Oil palm, rubber	Improved soil porosity, increased water retention	[31]

communities grow in the soil. This may affect how nutrients are exchanged, how much greenhouse gas is released into the atmosphere, and how much fertile soil is available. It is also important to understand the relationships between soil microbiota and biochar and their consequences for soil health, nutrient cycling, and long-term ecosystem sustainability.

6.2 Biochar utilization in agriculture and land management

Biochar improves soil moisture retention and water use efficiency in various environmental contexts. It is evidenced by real-world applications in land management and agriculture (Table 1). In Australia, agricultural systems utilize biochar to mitigate the effects of drought and water scarcity on crop productivity. For instance, an investigation of the impact of biochar additives on crop yield and soil water retention in vineyards was carried out in South Australia [81]. Previous research indicates that the use of biochar for water conservation shows adaptability to a variety of soil types, climates, and farming methods. In Sub-Saharan Africa, adding 10–20 t/ha of biochar to damaged soils have improved the drought resilience in key crops such as sorghum and maize by increasing water retention by 15%–25% [104]. In another study, biochar has increased the agroforestry yields in South America by improving moisture retention in heavily worn Oxisols by 10–15% [105]. Similarly, on acidic soils in Southeast Asia, applying 5–10 t/ha of biochar has enhanced the soil water-holding capacity by up to 12% and improved the plantation output of crops in water-scarce environments [29]. These regional examples from certain regions demonstrate how biochar can be used globally to alleviate water constraint and advance sustainable agriculture. The findings also showed that biochar enhanced the soil's ability to retain water and promoted vine growth and yield, especially in dry spells [106]. These results imply that, in water-limited settings, biochar amendments can improve soil moisture availability, and reduce the adverse effects of water stress on agricultural productivity.

Similarly, biochar is used for land management techniques in the United States to enhance soil water retention and reduce erosion in degraded ecosystems. For example, in dry and semi-arid areas, biochar has been used in land restoration efforts to improve soil fertility and encourage vegetation growth [42, 116]. A study conducted in the foothills of the Sierra Nevada in California showed that biochar enhanced the ability of soil to retain moisture and provide nutrients, which in turn promoted plant growth and biodiversity in the degraded land [76]. These findings demonstrate how biochar can restore damaged landscapes' ecological resilience and water-saving initiatives. The application of biochar in agroforestry and forestry systems has the potential to improve soil water retention as a part of sustainable land management techniques. For example, in Brazil, biochar was used for reforestation initiative to enhance water availability and soil fertility in damaged areas. A study conducted in Amazon examined how biochar amendments affect the characteristics of the soil and the growth of trees in degraded rainforest soils [117]. The results showed that biochar improved soil nutrient availability and water retention and promoted tree growth and ecosystem recovery.

Recently, Asia has seen a surge in the use of biochar in land management and agriculture due to its ability to increase soil fertility, retain more water, and promote sustainable farming methods. For example, smallholder farmers in India use biochar to combat challenges related to degraded soil and water scarcity [118], especially in arid and semi-arid areas of Haryana, Punjab, and many southern states. Although few pilot projects and training programs were conducted by the institutions in India; several agricultural research organizations promoted the application of biochar and showcased its benefits in better crop yield and good soil health [119] Its applicability on a larger scale in the country is required. Furthermore, Southeast Asian countries such as Vietnam and Thailand are investigating the potential of biochar to improve soil resilience to mitigate drought, and to lower the greenhouse gas emission [120]. According to studies conducted in these areas, biochar enhances the soil qualities, stores more water, and reduces dependence on chemical fertilizers. This makes the application of biochar to soil an effective and long-term approach to promote agricultural productivity while maintaining the environmental sustainability. For instance, studies on crop plantations have indicated that biochar can improve crop resistance to nutrient shortages and water stress and provide a viable approach to sustainable land management across Asia's varied agricultural environments [121]. Thus, it could be adopted in the rapidly depleting groundwater regions of north-western India. These findings suggest that biochar amendments can also support reforestation efforts and contribute to water conservation and ecosystem restoration in tropical forest ecosystems.

6.3 Effectiveness of biochar in different soil and climatic conditions

Variables, such as soil type, climate, biochar characteristics, and land management techniques, determine the effectiveness of biochar under diverse soil and climatic circumstances. For instance, a meta-analysis on the application of biochar to soils revealed higher soil water content and enhanced agricultural productivity in a range of crop varieties, climates, and soil types [30, 122, 123]. Biochar performs well in sandy and clayey soils due to its porous nature, which improves soil water retention and lowers the water loss through drainage and evaporation. Biochar also enhances soil aggregation and structure, facilitates improved water infiltration and dispersion throughout the soil profile, and enhances plant water absorption and drought tolerance.

The feedstock type, pyrolysis temperature, and application rate of biochar determines its effectiveness in certain soil and climatic conditions. The porosity, surface area, and nutrient content of biochar produced from various feedstocks at different pyrolysis temperatures might fluctuate the biochar's ability to water retention and its agronomic performance. Researchers have examined how biochar affects water retention in two distinct types of soil used for growing maize [122]. Although, the best way to apply biochar varies based on crop type, climate, and soil properties. In general, higher application rates tend to yield greater benefits in crop productivity, and soil moisture retention.

Interactions with soil bacteria and nutrient cycling processes also affect the efficiency of biochar in various soil, and climatic conditions. For soil microorganisms, biochar provides them a home and a carbon source, which affects their composition and activity [31, 124]. Studies have demonstrated the potential of biochar amendments to augment soil nutrient cycle processes, foster beneficial microbial activity, and increase microbial diversity and abundance [124]. However, depending on the type of soil, climate, and land management techniques, biochar may have different impacts on the microbiota in the soil and the dynamics of nutrients. Further research is required to elucidate the relationships between soil microbiota and biochar, as well as how they affect soil health, nutrient cycling, and ecosystem functioning across diverse environmental conditions.

6.4 Economic viability for farmers

The economic viability of biochar as a soil amendment presents a promising opportunity for enhancing farm-level profitability and sustainability. Biochar, produced from locally accessible agricultural waste and applied in appropriate quantity, can greatly enhance crop yield, soil health, and nutrient usage efficiency while lowering the input costs of chemical fertilizers [125]. Its long-term advantages, such as improved soil structure and water retention, also support consistent agricultural production. When biochar production costs are minimized and application rates are adjusted to optimize agronomic results without experiencing diminishing returns, it becomes financially appealing. Its economic value is further enhanced by the potential to earn income through carbon sequestration incentives [126]. However, a number of variables, including feedstock availability, production technology, market accessibility, and institutional backing influence the feasibility of biochar utilization.

In a study conducted by Patel and Panwar [127], it was observed that a biochar application rate of 8 t/ha was found to be optimal, offering the highest economic returns with a benefit-cost ratio of 1.48, a net present worth of $932.85/ha, and an internal rate of return as 85.71%. While biochar production and application entail initial costs, these are outweighed by long-term agronomic and financial benefits, particularly when they are produced on-site using agricultural residues. However, higher application rates beyond 20 t/ha were economically unviable. These findings suggest that moderate and well-calibrated use of biochar can play a significant role in promoting sustainable agriculture and environmental stewardship, provided there is adequate policy support, cost-effective production systems, and greater farmer awareness.

7 Challenges and future directions

7.1 Limitations and knowledge gaps

A study on the long-term impact of biochar on soil moisture dynamics, plant-water relations, and ecosystem functioning across diverse soil types and climatic conditions is required to fully understand the exact impact of biochar on water-saving applications. Several studies have demonstrated the potential benefits of biochar in improving water use efficiency in agricultural systems [28, 128]. However, the mechanisms underlying these effects and their interactions with soil microbiota and nutrient cycling processes are poorly understood. Additionally, the synthesis, characterization, and use of biochar lack standardized techniques, further complicating the comparison of study results and the extrapolation of findings to practical use. Further research is required to fill these knowledge gaps and identify optimal conditions for applying biochar, which can optimize its efficacy in water-saving practices while reducing possible environmental concerns and trade-offs.

For cost-effectiveness, environmental effects, and long-term sustainability of biochar applications, analysis of the technical economy and life cycle analysis (LCA) of biochar is essential. The technical economy considers the financial viability of producing biochar by taking into account the expenses for pyrolysis, transportation, and feedstock sourcing in addition to possible income from carbon credits, soil enhancement, and water conservation benefits. However, LCA evaluates biochar's environmental performance throughout its entire lifecycle, including feedstock collection, production, application, and final soil degradation [129, 130]. These studies demonstrate how biochar can reduce greenhouse gas emissions, enhance resource efficiency, and sequester carbon. They also support the development of sustainable and scalable biochar solutions for environmental management and agriculture by determining trade-offs and improving production techniques.

7.2 Future research and technological advancements

Subsequent investigations and technological developments may focus on approaches to maximize the effectiveness of biochar in water-saving scenarios and improve its sustainable application in agriculture and environmental management. More study is required to deepen our understanding of the mechanisms that underlie the effects of biochar on soil-water dynamics, plant-water connections, and ecosystem functioning across various soil types and climates. This includes examining how soil microbes, nutrient cycling, and soil structure interact with biochar and how it can improve soil organic matter and carbon sequestration. Along with improving microbial activity, water retention, and fertility; biochar's solid carbon structure enables efficient carbon sequestration, which reduces greenhouse gas emissions and improves long-term soil health. However, the use of low-quality feedstock may result in nutrient imbalances, unanticipated change in soil microbial populations, and the possible release of pollutants. Future studies should also focus on developing standardized procedures for manufacturing, characterizing, and using biochar to maintain uniformity and repeatability across studies.

Enhancing the scalability and effectiveness of biochar can also be facilitated by technological advancements in production processes. This includes creating novel pyrolysis techniques to produce biochar with improved stability and customized characteristics, such as hydrothermal carbonization and rapid pyrolysis techniques. Moreover, improvements in biochar activation methods, both chemical and thermal activation, can enhance the material's surface area and pore structure. It may improve the capacity to retain water and adsorb nutrients. Biochar production systems can become more environmentally and economically sustainable by integrating them with other sustainable biomass usage technologies, such as waste management and bioenergy production. Despite many advantages, biochar still faces many challenges and therefore, its use is limited on a local level. Brantley et al. [131] compiled the long-term adverse effects of biochar, noting that its unscientific use can have implications on soil fertility, soil loss, and soil salinity. Similarly, Xiang et al. [132] highlighted that biochar can pose potential environmental risks to soil, sediments and, aqueous environments.

Future studies should examine the possible trade-offs and interactions between applying biochar and other potential techniques for managing water and soil, such as conservation tillage, crop rotation, and cover crops. Maximizing water and nutrient management in agricultural system involves examining the combined impacts of biochar with organic and inorganic soil amendments, microbial inoculants, and precision irrigation techniques. Research should focus on the long-term effects of applying biochar on soil health, agricultural productivity, and ecosystem resilience, considering variables including biochar stability, land use history, and climate change projections. By addressing these research goals and technological advancements, one may effectively harness the full potential of biochar as a sustainable solution for water conservation and environmental management in the context of climate change and resource scarcity.

8 Conclusion

This study emphasizes the potential application of biochar as a sustainable approach to water conservation under changing climatic conditions. The study shows that biochar additives can improve soil moisture retention, water infiltration rates, and water use efficiency across various agricultural and environmental contexts. Biochar offers significant potential to reduce the negative effects of drought, soil erosion, and water shortage on crop productivity and ecosystem resilience by improving soil structure, enhancing nutrient retention, and fostering positive interactions with soil microbes. Policymakers, researchers, and practitioners are encouraged to prioritize future studies on the effectiveness and optimization of biochar. Such research would support the development of customized guidelines for the application of biochar and land management practices, while promoting interdisciplinary collaborations to facilitate knowledge exchange and technology transfer for sustainable water conservation and agricultural development in a changing climate. These recommendations highlight the importance of integrated soil and water management approaches.

Author contributions

Prabhakar Sharma conceived and planned the study, wrote and reviewed the manuscript, and prepared the figures. Shakir Ali modified the figures, and reviewed and edited the paper. Anamika Shrivastava and Krishna Kumar Yadav wrote and reviewed the paper.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

The authors declare no competing interests and have complied with the ethical standards given by the journal. No human or animal subjects were involved in this research.

Consent for publication

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