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Review Article

Biochar a promising amendment to mitigate the drought stress in plants: review and future prospective

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Abstract

Drought stress (DS) is one of the most destructive abiotic stresses that negatively affects plant growth, and yield. The intensity of DS is continuously increasing due rapid of water sources, less rainfall, and an increase in global warming. The world's population is increasing at an alarming rate which needs a substantial increase in crop production to meet global food needs. Therefore, in this context, we must have to increase crop production in the scenarios of rapid climate change and increasing intensity of abiotic stresses. Globally, different measures are used to mitigate the adverse impacts of DS, recently biochar (BC) has emerged as an excellent soil amendment to mitigate the toxic effects of DS and improve crop production. The application maintains membrane integrity, plant water relations, nutrient homeostasis, photosynthetic performance, hormonal balance and osmolytes accumulation, and gene expression thereby improving plant performance under DS. Moreover, BC application under DS also improves soil organic matter, water holding capacity, soil structure stability, and activity of beneficial microbes which can improve the plant performance under DS. In

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the present review different mechanisms through which BC mitigates the adverse impacts of DS on plants are discussed. This review provides new suggestions on the role of BC in mitigating the adverse impacts of DS.

Keywords: biochar; drought stress; hormones; photosynthesis; plant water relations

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Introduction

The global population is continuously soaring with a substantial increase in food demand. It is expected that the world's population will be increased by 50% by the end of 2050 therefore, it is mandatory to increase food production to meet the rising food needs (Robertson *et al*., 2023). However, rapid climate change, global warming, and the onset of abiotic and biotic stresses are the most impact factors negatively affecting global crop production (Ahmadalipour *et al*., 2019; Zhang *et al*., 2022). Water shortage is increasing in the main parts of the world owing to climate change, mishandling of water sources, and declining rainfalls which has an unfavorable impact on crop production (Abdelkhalik *et al.,* 2019; Besser *et al.,* 2021). Water deficiency is drought stress (DS) and it can severely reduce plant growth and development (Toscano et al., 2023). Drought stress induces cell dehydration, reduces nutrient uptake, disrupts hormone production, damages membrane integrity, and decreases photosynthesis thereby causing a marked reduction in plant growth (Khan *et al.*, 2010; El-Mogy *et al.,* 2022).

Drought stress is a major limiting factor for plant growth and productivity because it negatively affects different physiological and biochemical processes in plants (Ma *et al.,* 2019; Barros *et al.,* 2021). Water deficiency impacts cell division, elongation, differentiation, osmotic adjustment, loss of cell turgor, and disturbed energy balance therefore causing a reduction in plant growth (Hou *et al.,* 2020). Further, DS also induces the stomata closing which reduces the water losses to prevent dehydration however, it induces CO_2 limiting therefore detrimentally affecting the photosynthesis (Flexas *et al*., 2009). Photosynthesis is fundamental to plant growth however, plants' ability to retain photosynthesis largely depends on environmental conditions (Walczyk and Hersch-Green, 2022). Drought stress is a real challenge for plant scientists to fulfill food demands (Zhu *et al*., 2010). Plants are subjected to water deficiency when the supply of water to roots is restricted or the water loss transpiration is increased (Anjum *et al.,* 2011). Therefore, imbalanced water uptake causes oxidative stress by increased reactive oxygen species (ROS) production that damages the proteins, lipids, and DNA and causes a substantial reduction in plant growth and development (Cotado *et al.,* 2020; Lin *et al.,* 2022). Plants adopt different mechanisms to counter the toxic effects of DS. Likewise, plants maintain the turgor pressure by increasing osmotic adjustment and cell elasticity and decreasing cell size by protoplasmic resistance (Takahashi *et al.,* 2021). Besides these plants also activate the antioxidant defense system and accumulate osmolytes that ensure the plant's survival under DS (Hassan *et al.,* 2020).

Biochar (BC) has evolved as a key player in improving crop growth and development under normal and stress conditions (Moragues *et al*., 2023; Tang *et al.,* 2022). Biochar has a high exchange cation exchange capacity, alkaline nature, nutrient availability, and water-holding capacity thus it improves plant growth under stress conditions (Lashari *et al*., 2013). The application of BC also improves water use efficiency (WUE), nutrient uptake, carbon assimilation, and antioxidant activities thus ensuring better plant growth under water deficit conditions (Singh *et al*., 2019; Wang *et al*., 2020). Biochar also improves chlorophyll synthesis, is stomata conductive, maintains membrane stability, and prevents excessive production of ROS that ensures better plant growth under DS (Haider *et al*., 2020). Moreover, BC also induces favourable impacts on soil physiological and biochemical properties therefore improving the impact growth under DS (Agbna *et al*., 2017). In the current review, we have provided information on different mechanisms by which BC mitigates deleterious impacts on DS on plants. This is the first in-depth evaluation of the contribution of BC to DS mitigation, and it will advance our understanding of BC's current contribution to DS mitigation.

Effect of drought stress on plants

Drought stress negatively affects plant growth by affecting various plant functions including photosynthesis, transpiration, nutrient uptake, water potential, sugar and nutrient metabolism, and antioxidant and osmolytes synthesis (Figure 1, Singh *et al.,* 2021). Plants activate different genes and induce cellular signaling that causes plants to under different physiological and biochemical responses (Tovignan *et al.,* 2020). Water deficiency decreases cell growth, induces stomata closure, and reduces cell turgor, leaf water contents, and nutrient absorption therefore causing a reduction in plant growth (Tarafdar *et al.,* 2022). The plant's physiological responses to drought stress can be either short-term or long-term. The long-term impact of DS on plant processes includes disruption of physiological cycles, change in maturity, and yield losses (Demidchik, 2018). On the other hand, short-term effects of DS include a reduction in stomata conductivity, water potential nutrient, nutrient and water uptake, and turgor pressure (Batool *et al.,* 2018). Plants send positive and negative signals between roots and shoots to adapt to environmental conditions (Roblero *et al.,* 2020; Hassan *et al.,* 2021).

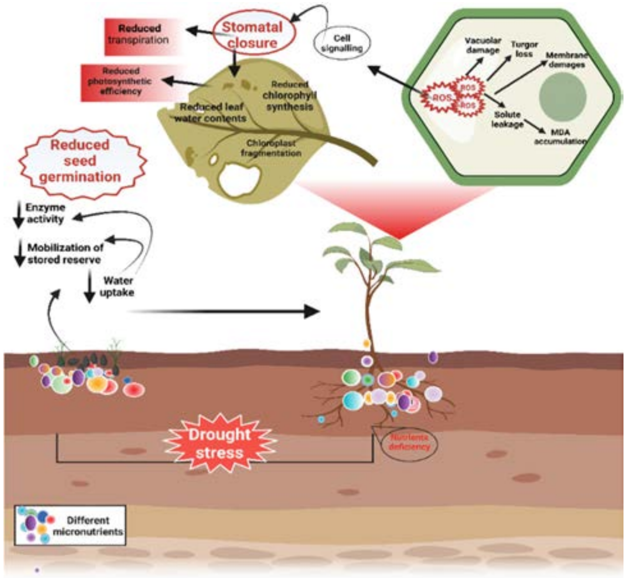

Figure 1. Drought stress reduce the seed germination, enzymatic activities, photosynthetic activities, nutrients uptake and increases membrane damage, osmolytes accumulation ROS production therefore, cause reduction in plant growth

Plants also produce many osmolytes and hormones abscisic acid (ABA), auxin, cytokinins, ethylene, gibberellins, and proline that works as signaling molecules and regulate the plant physiological processes under DS (Mittler and Blumwald, 2015; Yamada and Umehara, 2015; Wang *et al*., 2020). DS also induce ROS production that affects various plant metabolic and physiological responses and certain ROS works as signaling molecule in plants' adaption against stress conditions (Jaspers and Kangasjärvi, 2010; Oğuz *et al*., 2022). The plant's first physiological response under drought stress is the reduction in transpiration by stomata. The stomata closing and reduction loss of water is an important plant response to avoid the negative effects of DS (Chaves *et al*., 2009). Stomata closing also affects leaf water contents, chlorophyll synthesis, chloroplast fragmentation, gas exchange, nutrient, and water uptake (Table 1) and also suppresses the leaf morphology

(Fahad *et al*., 2017). All these processes directly and indirectly affect photo-synthesis and therefore, cause a reduction in plant growth and development (Muhammad *et al*., 2021). The stomata closing prevents carbon dioxide (CO_2) use which has a great impact on photosynthesis (Sevanto, 2014) and the reduction of CO_2 uptake causes substantial loss in photosynthetic activity (Flexas *et al*., 2004).

Table 1. Effect of drought stress on growth, physiological and biochemical functions of different plants

Plant species	Drought conditions	Major effects	References
Brassica	40% FC	DS reduced the root and shoot growth, leaves, RWC, SPAD chlorophyll contents, photosynthetic and transpiration rate, stomata conductance, and increased MDA and H_2O_2 production.	Li *et al.* (2023)
Wheat	45% FC	DS leads to significant reduction in growth traits, leaf length, root length root volume and increased MDA, H_2O_2 and antioxidant activities	Zhang *et al.* (2023)
Chickpea	40% FC	Drought reduced leaves, flowers, pods, RWC, chlorophyll contents and increased EL, proline and GB concentration.	Keerthi *et al.* (2023)
Maize	50% FC	A significant reduction in chlorophyll contents, RWC and growth traits was observed with DS, while DS increased MDA, EL and proline production.	Kavian *et al.* (2013)
Wheat	40% FC	Water deficiency reduced the photosynthetic and transpiration rates, stomata conductance, CO_2 concentration, stomata length and increased soluble sugars and AsA, GSH and GSSG activity.	Jing *et al.* (2023)
Maize	25% FC	Water stress reduced the membrane stability, RWC, total soluble proteins, yield and yield traits and increased MDA production.	Mansour *et al.* (2023)
Mungbean	40%	Water deficit conditions reduced RWC, photosynthetic and transpiration rates, stomata conductance, chlorophyll contents, WUE, plant height, branches/plant, pods, and seed yield	Tamanna *et al.* (2023)
Maize	35% FC	Water deficiency reduced the root and shoot growth, root hydraulic conductivity, photosynthetic and transpiration rates stomata conductance, and increased EL, MDA and H_2O_2 production.	Gong *et al.* (2023
Rice	50%	Drought conditions caused reduction in photosynthetic and transpiration rates, chlorophyll contents, plant height, panicles production, grain yield and increased H_2O_2 production, APX, CAT and SOD activities.	Khan *et al.* (2023)
Wheat	50%	Water deficit conditions reduced dry matter production, RWC, chlorophyll contents, yield and increased proline, soluble sugars, soluble proteins, MDA, CAT, POD and SOD activity.	Ning *et al.* (2023)

MDA, malondialdehyde, H_2O_2: hydrogen peroxide, EL: electrolyte leakage, AsA: ascorbic acid, GSH: glutathione, GSSG: glutathione disulfide, CAT: catalase, POD: peroxidase, SOD: superoxide dismutase.

Further reduction in transpiration owing to stomata closing under DS also limits the uptake of nutrients and their translocation (Amin *et al*., 2014) and this situation causes a reduction in nutrient concentration in plant tissues (Ahanger *et al.,* 2016; Rivas *et al*., 2016). Moreover, reduced water uptake due to DS also reduced the relative water content (RWC) and caused a reduction in plant physiological functioning (Hartmann *et al.,* 2013). Plant leaf water potential is important for plants' survival and photosynthetic processes (Alghabari *et al.,* 2015). However, DS significantly reduced the leaf water potential which caused a reduction in plant photosynthetic efficiency (Sun *et al.,* 2013). Photosynthesis is the most important process of plants as it directly impacts growth, development, and yield (Ashraf and Harris, 2013). Chloroplast is an important organelle for photosynthesis; however, DS deteriorates the structure of chloroplast which adversely affects chlorophyll synthesis (Ashraf and Harris, 2013; Sun *et al.,* 2014). The decrease in chlorophyll synthesis is a typical manifestation of oxidative stress (Faisal *et al.,* 2019) and the reduction of chlorophyll synthesis under DS occurs due to photo-oxidation and degradation of chlorophyll (Nezhadahmadi *et al.,* 2013).

Drought-induced higher ROS production damages plants various physiological and metabolic processes (Zou *et al.,* 2021). However, in response to coping with ROS plants activate excellent antioxidant defense systems to tolerate the negative effects of DS (Hossain *et al.,* 2013). Besides these plants also produce various osmolytes that protect them from the damaging effects of DS. These osmolytes also regulate the osmotic balance, maintain water flow stabilize membranes, and prevent the accretion of stress-free radicles (Padmavathi and Rao, 2013). Among different osmolytes; proline is an important amino acid that possesses excellent antioxidant properties and it plays an important role in preventing cell death (Bhardwaj and Yadav, 2012; Mwadzingeni *et al.,* 2016). Likewise, glycine-betaine (GB) is also an important osmolyte and it protects protein unfolding and denaturation (Giri, 2011). Besides these plants also accumulate mannitol, sucrose, and trehalose which also protect plants by scavenging effects of ROS (Zhang *et al.,* 2020a).

Biochar production processes

The biochar production process has a strong impact on the final characteristics of BC. Pyrolysis is an important process used in BC production which involves the conversion of biomass in oxygen-starved conditions. Generally, pyrolysis results in the production of bio-oil, syngas, and biochar (Bruun *et al.,* 2012). The pyrolysis process is carried out in the presence of inert gas typically nitrogen (Weber and Quicker, 2018). In pyrolysis different polymers like cellulose, hemicellulose, and lignin present in biomass are breakdown under the influence of heat (Wang *et al.,* 2020b). It is been documented that slow pyrolysis produces more BC and less syngas and bio-oil while fast pyrolysis produces less BC and more syngas (Roy and Dias, 2017). It is important to note that BC properties are not always homogenous even if the production method is similar (Zhao et al., 2013). Pyrolysis temperature is an important factor that affects BC surface area pH, similarly, feedstock type also affects the BC organic carbon and nutrient concentration (Zhao *et al.,* 2013; Esfandbod *et al.,* 2017).

Generally low pyrolysis temperature (below 550 °C) produces BC with low ash contents and it shows less crystalline structure (Gruss *et al.,* 2019). BC yield is manipulated by feedstock selection processes (Yoshida et al., 2008) and BC yield largely depends on the type of feedstock and the temperature of pyrolysis. The increase in pyrolysis temperature decreases BC yield while it increases bio-oil yield and it is been also documented that pyrolysis temperature above burns off most nitrogen, potassium and sulfur molecules (Joseph *et al.,* 2010). Co-pyrolysis is also used to produce BC and it involves pyrolysis of two feedstocks (Agegnehu *et al.,* 2017). Hydrothermal carbonization (HTC) is also another important process used to produce hydrochars which can also be used as a soil amendment (Allohverdi *et al.,* 2021; Paul *et al.,* 2018).

Soil application of biochar

Due to the addition of organic matter and organic carbon, the application of BC considerably increased the soil quality and fertility (Heitkötter and Marschner, 2015). Different particle sizes are needed for the maintenance of water holding capacity (WHC) along with a certain aeration level (Heitkötter and Marschner, 2015). BC application can remediate the structure of poor soils and application of BC to compacted soils ensures better aeration owing to appreciable porosity of BC (Heitkötter and Marschner, 2015). Biochar also has a large surface area and higher porosity (Dempster *et al*., 2012), therefore, field application of BC improves the growth and yield of crops by improving nutrient and water uptake (Agegnehu *et al*., 2017). Biochar application to soils results in a greater amount of oxidation and reduction reactions which release the nutrients and ensure better plant growth. Biochar can also persist in soil over a long time therefore, there is no need to re-apply the BC years which makes it cost cost-effective soil amendment (Joseph *et al.,* 2010). Moreover, over time soil organic matter (SOM) is diminished due to weathering, anthropogenic activities, and cultural practices (Allohverdi *et al*., 2021).

In this context, structure of biochar makes it particularly stable and withstands in soils over a long time (Sohi *et al*., 2010). Additionally, BC also increases the ethylene level in plants and this increase can significantly increase the crop yield (Spokas *et al*., 2010).

Biochar a key player against drought stress

Biochar is an important soil amendment to mitigate the adverse impacts of DS (Siebielec *et al*., 2020). Biochar is known as a black gold of agriculture and its application under DS improves soil moisture, nutrient uptake, and cation exchange capacity (CEC) and brings favorable changes in plant physiological and biochemical processes thus ensuring better plant growth (Zheng *et al*., 2019; Odugbenro *et al*., 2020). In given below section we have provided a detailed discussion on how BC can mitigate the adverse effects of DS.

Biochar improves water uptake and protect the membranes to induce drought tolerance

Drought stress is a significant abiotic stress that negatively impacts plant membranes and results in cytoplasmic dehydration lipid peroxidation and electrolyte leakage (Hassan *et al.,* 2021). The application of BC has been reported to decrease lipid peroxidation by decreasing the ROS which ensures better membrane stability and results in EL and better RWC (Hafez *et al.,* 2020). BC also reduces MDA production owing to better antioxidant activities and osmolytes accumulation which also ensures better membrane integrity (Yildirim *et al.,* 2021). BC also enhanced WUE and water uptake which ensures better RWC and subsequent plant growth under water deficit conditions (Mannan *et al.,* 2021). Further, BC application also possesses excellent water-holding capacity which improves the water uptake and results in better leaf water contents under DS (Licht and Smith, 2017). Other authors also found that BC application improved plant available water, RWC which induces positive impacts on photosynthesis, leaf transpiration, and other plant functioning under DS (Licht and Smith 2017). Likewise, the study findings of Ahmad showed that BC application (2% and 3%) improved leaf water potential, and study findings of Haider *et al.* (2015) depicted that BC improved RWC in sandy soil. Additionally, BC strengthens the antioxidant defense systems, and improves membrane stability and RWC, however, it depends on water uptake, soil type, and BC type (Lyu *et al.,* 2016).

Biochar improves nutrient uptake to counter effects of DS

Drought stress disturbs nutrient uptake and causes yield losses, nonetheless, BC is an important soil amendment that improves nutrient uptake and ensures better plant growth under water deficit conditions (Figure 2). For example, Muhammed *et al.* (2020) found that BC applied at the rates of 0.75% and 1.5% significantly improves N uptake while according to Ibrahim et al. (2020b), BC improves plant performance by acting as a slow-release N fertilizer. Biochar-mediated increase in N uptake is associated with improved soil CEC owing to the fact higher soil CEC has a better capacity for NH^{4+} and N utilization (Liang *et* *al.,* 2020). The study findings of Glaser *et al.* (2002) showed that BC application to DS conditions improved calcium (Ca), magnesium (Mg), and potassium (K) availability while Van Zwieten *et al.* (2010) discovered that adding BC to the soil altered the pH thereby increasing the availability of nutrients. Likewise, other researchers found that BC improved the nitrogen (N) uptake and offset the effects of DS (Zheng *et al.,* 2018) and Zoghi *et al.* (2019) noted that BC improved nutrient uptake by increased WUE and CEC under DS. In another study, Egamberdieva *et al*. (2017) noted that combined BC and *Bradyrhizobium* application improved N and P while Liu *et al.* (2017) found BC made from birch wood in combination with *Rhizophagus irregularis* decreased N and P uptake.

In a study to investigate the impact of BC on nutrient uptake under DS, Ahin et al. (2016) discovered that BC increased N uptake and Durukan *et al.* (2020) found that BC application to sugar beet plants improved P concentration. These authors also suggested that the rate of BC plays an important role in nutrient uptake and they found a significant increase in nutrient uptake with increase BC application rate. In another study, Langeroodi *et al.* (2019) applied different rates of BC (0, 5, 10, and 20 t ha-1) to pumpkin plants growing under DS and found that BC increased the Mg concentration with an increase BC rate. The study findings of Poormansour *et al.* (2019) showed that BC application (1.25%, 2.5%, 3.75%, and 5%) to *faba bean* plant under DS conditions resulted in increased absorption of Ca and Mg as well as their content in soil.

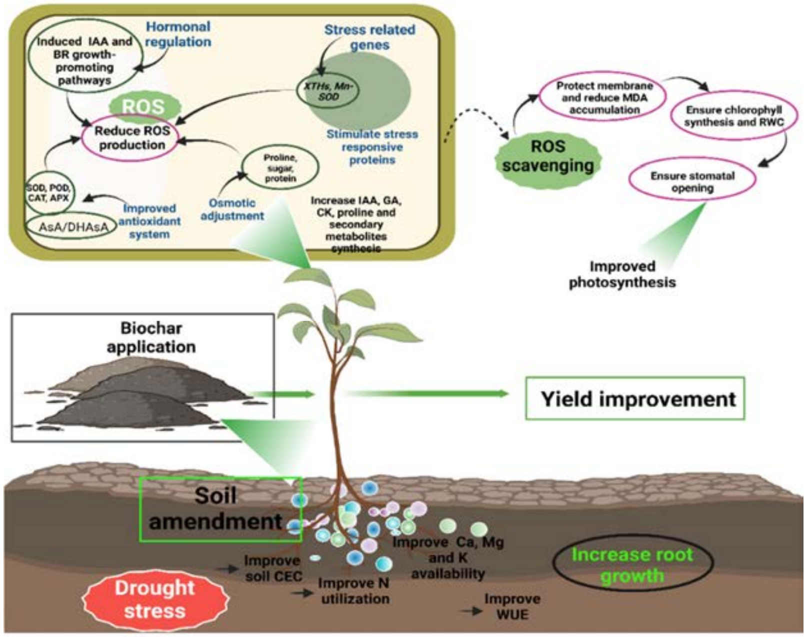

Figure 2. Biochar application improves antioxidant activites, nutrient uptake, photosynthesis, chlorophyll synthesis, stomata opening, hormoe and osmolyte balance and reduce ROS production which in turn increases plant growth under DS

Biochar protects photosynthetic apparatus to ensure better photosynthesis under DS

Photosynthesis is one of most important physiological processes in plants, however, water deficiency substantially reduced the photosynthesis by decreasing electron transport, leaf area and synthesis of chlorophyll. The application of BC decreased the negative effects of DS and improves photosynthesis by increasing leaf area, chlorophyll synthesis and electron transportation (Manolikaki and Diamadopoulos, 2019). Due to a significant increase in chlorophyll synthesis and a decrease in stomata conductance, biochar application also buffers the effect of DS on carbon assimilation and photosynthesis (Lyu *et al.,* 2016; Wang *et* *al.,* 2021). It has been documented that under water deficiency BC application increased WUE which in turn increased rate of photosynthesis and reduce non-stomatal limitation (Paneque *et al.,* 2016; Farooq *et al.,* 2021). Further, BC application reduce the drought induce ROS production which in turn increases photosynthetic rate (Gharred *et al.,* 2022). Moreover, BC also improves stomata length, width and density which leads to considerable increase in WUE and photosynthesis under DS (Khan *et al.,* 2021). The use of BC under drought conditions improves leaf water relation which is also an important reason of BC mediated increase in photosynthesis and transpiration rates under DS conditions (Haider *et al.,* 2015). In a different study, Kammann and Graber (2015) discovered that BC supplementation increased assimilate production under DS, enhanced soil characteristics, and improved leaf water status. Similarly, Lyu *et al.* (2016) discovered that the addition of BC increased antioxidant and electron transport activities, reducing the harmful effects of drought and increasing plant photosynthetic efficiency under DS.

Biochar maintains better osmolytes and hormonal synthesis to counter the effects of DS

Osmolytes serve an essential role in preventing DS, but DS alters the hormonal balance osmolytes accumulation, which has a detrimental impact on plant performance. Proline is an important osmolyte produced under DS and it acts as a ROS scavenger.

For example, in drought-stressed *M. ciliaris* leaves proline concentration was significantly increased however, BC treatment lowered the synthesis of proline, possibly as a result of decreased ROS production, decreased osmotic stress, and decreased oxidative damage in BC-treated plants (Yildirim, 2021). Other researchers discovered that BC and chitosan together reduced the levels of starch, soluble carbohydrates, and sucrose (Hafez *et al.,* 2020). Conversely, Gullap *et al.* (2022) found that drought stress reduced the gibberellins (GA) and indoleacetic acid (IAA) and increased the ABA concentration, however, BC application increased GA and IAA synthesis and reduced the ABA concentration to counter the toxic effects of DS (Table 2). Further Khan *et al.* (2021) noted that BC application increased the total soluble proteins (TSP) free amino acids (FAA) and proline synthesis which countered the toxic effects of DS. In another study combined use of AMF and BC countered the toxic effects of DS by increasing osmolytes synthesis, maintaining hormonal balance and antioxidant activity (Mickan *et al.,* 2016). Therefore, BC maintains the osmolytes and hormones accumulation which protect plants from the damaging impacts of drought and improve plant performance under DS.

Table 2. Effect of biochar application on growth, physiological and biochemical functions of plants to induce drought tolerance

Plant species	Drought conditions	Biochar application	Major effects	References
Soybean	25% FC	10 g kg^{-1}	Biochar application increased stomata conductance, CO_2 concentration, WUE, root and shoot biomass and grain yield.	Zhang *et al.* (2020)
Wheat	30% FC	37.18 g kg^{-1}	The application of BC increased plant height, tillers, grain weight, biological and grain yield, WUE and leaf chlorophyll contents.	Haider *et al.* (2020)
Rapeseed	40% FC	60 t ha^{-1}	Biochar addition increased chlorophyll contents, plant height, 1000 GW, grain yield, oil and protein contents, gas exchange characteristics, CAT, POD, SOD and proline synthesis and reduced EL, MDA, H_2O_2 contents.	Khan *et al.* (2021)
Tomato	70% FC	100 g kg^{-1}	The addition of BC increased soil water contents, plant WUE, plant water relations, gas exchange	Zhang *et al.* (2023b)

			characteristics, leaf growth, biomass production and reduced ABA production.	
Cabbage	50% FC	10% BC	BC reduced toxic impacts of drought and improved stem diameter, plant height, plant fresh weight, chlorophyll concentration, RWC, leaf gas exchange properties, CAT, SOD, POD activities, sucrose concentration, and NPK, Ca and S uptake.	Yildirim *et al.* (2021)
Wheat	Drought was applied by skipping irrigation at tillering and grain filling stage.	38 g kg^{-1}	BC application under DS increased plant height, 1000 GW, spike length, grain yield, NPK uptake, soil organic carbon, and microbial biomass carbon and soil enzymatic activities.	Zaheer *et al.* (2021)
Wheat	35% FC	20 g kg^{-1}	The application of BC increased root growth, root biomass, chlorophyll synthesis, photosynthetic characteristics, proline synthesis, reduced EL, MDA and H_2O_2 production,	Lalarukh *et al.* (2022)
Chickpea	50% FC	30 g kg^{-1}	BC supplementation increased root and shoot growth, primary and secondary branches, nodule length, photosynthetic pigments, NP uptake, and stomata density.	Hashem *et al.* (2019)
Barley	30% FC	25 g kg^{-1}	BC application to drought stress plants improved, root and shoot biomass, seed germination, chlorophyll synthesis, POD, CAT and SOD activities and NPK uptake.	Gul *et al.* (2023)
Soybean	30%	20 g kg^{-1}	BC mitigated the adverse effects of drought by increased root and shoot growth, leaf chlorophyll contents, stomata conductance, photosynthesis and transpiration rate, CAT and SOD activities and increased 1000 GW and grain yield.	Nawaz *et al.* (2023)

WUE: water use efficiency, NPK: nitrogen, phosphorus and potassium, Ca: calcium, S: sulfur, ABA: abscisic acid

Biochar increases antioxidant activities to counter oxidative damages

Water deficiency cause oxidative stress by increasing the formation of ROS, which harms important molecules. Plants have, however, evolved a superb antioxidant defense system to combat the damaging effects of DS. For example, in *Medicago* plants grown under DS showed an increase in superoxide dismutase (SOD) activity which improved the membrane stability and provided photo protection to plants (Gharred *et al.,* 2022). Further, BC also improves the antioxidant activities and increase in ascorbate peroxidase (APX) and SOD activity has been observed with BC application (Gharred *et al.,* 2022). Additionally, BC treatment mitigates the harmful effects of DS on plants by boosting antioxidant activities (Chaves *et al.,* 2009). In a study, Foyer and Noctor (2009) and his coworkers discovered that drought-stressed plants had increased AsA/DHAsA ratios and SOD, APX, glutathione peroxidase (GPX), and glutathione reductase (GR) activities, but these activities were insufficient to counteract the harmful effects of DS. Nonetheless, BC application (2%) appreciably increased AsA/DHAsA ratio, SOD, APX, GPX, and GR activities which countered the oxidative damages (Foyer and Noctor, 2009). Moreover, Zulfiqar *et al.* (2022) also found a significant increase CAT, POD and SOD activities owing to BC application which in turn improved plant functioning cell growth and reduced the toxic effects of ROS (Zulfiqar *et al.,* 2022). Barley plants given BC showed a noticeable boost in their CAT, POD, and GR activities as well, which mitigated the damaging consequences of oxidative damage

(Hafez *et al.,* 2020). Therefore, reduction of ROS and protection of plants from the negative effects of drought stress caused by BC-mediated increases in antioxidant activities boost plant development under drought stress.

Biochar improves genes expression to counter effects of DS

BC improves the gene expression which can counter the toxic effects of DS in plants (Table 2). For example, drought-stressed barley plants showed an increase CAT, APX and Mn-SOD gene expression under 50% FC as compared to 75% and 100% FC, and BC application reduced the expression level of these aforementioned proteins under DS (Hafez *et al.,* 2021). Racioppi *et al.* (2019), on the other hand, discovered that BC treatment boosted the expression of CAT, APX, and Mn-SOD genes, which in turn reduced the harmful effects of DS. Other researchers also found that BC application activated the auxin-responsive growth-promoting pathway which stimulated plant growth under DS (Vissenberg *et al.,* 2005). Xyloglucan endotransglucosylase/hydrolase (XTHs) genes control the extensibility of the cell wall (Sánchez-Rodríguez *et al.,* 2010) and according to Racioppi *et al.* (2019), the expression of these genes is increased by the administration of BC which stimulates plant development under DS. According to Viger *et al.* (2015), BC stimulates IAA and BR growth-promoting pathways, which in turn work to counteract the harmful effects of DS and promote improved plant growth by activating Ca^{2+} and ROS-mediated cell signaling. There are limited studies available in the literature about the role of BC in mitigating DS, therefore, more studies must be conducted on this aspect for the promising future of BC in mitigating DS.

Biochar nutrition improves plant performance under drought stress

Drought stress reduces the plant's growth through different mechanisms including reduction in photosynthesis, nutrient uptake, and increased osmotic and oxidative damage. Nonetheless, BC has been reported to improve osmolytes accumulation, nutrient uptake, and antioxidant activities which can counter the toxic effects of DS in plants (Gharred *et al.,* 2022). Okra and maize plants growing under DS with BC showed a marked increase in growth, similarly, wheat plants under semi-arid conditions also showed a significant increase with BC (Haider *et al.,* 2015; Olmo *et al.,* 2014). Biochar application increases leaf area which maintains optimum nutrient supply and, therefore, ensures better plant growth under water deficit conditions (Zheng *et al.,* 2021). BC application also ensures better vegetative and reproductive growth and quality owing to a reduction in the toxic effects of osmotic and oxidative damage (Agbna *et al.,* 2017). Moreover, other authors found BC could increase the growth of water-stressed plants by increasing photosynthesis, plant water relations and uptake of nutrients (Haider *et al.,* 2015; Egamberdieva *et al.,* 2017).

Another study found that whereas BC application rates >60 t ha^{-1} had negative impacts on rapeseed growth and seed production under DS, however, BC treatment rates between 0 and 30 t ha^{-1} increased biomass and yield. Further BC application increased biomass, pods/plant, and 1000 seed weight by 23%, 32%, and 21% under DS (Khan *et al.,* 2021) and BC treatment (0-30 t ha^{-1}) raised biomass, pods/plant, and 1000 seed weight by 56%, 26%, and 15% in control conditions. DS also had a deleterious impact on the oil and protein levels, although BC significantly improved these components under DS (Khan *et al*., 2021).

Biochar improves soil characteristics to improve DS tolerance

Biochar is a fantastic tool to improve soil health and crop productivity. According to reports, BC enhances the physical characteristics of soil under DS, such as soil density, soil moisture levels, and aggregate stability (Figure 3: Bamminger *et al.,* 2016; Zhang *et al.,* 2017). According to Zhang *et al.* (2017), BC enhanced the soil's characteristics and bacterial population, which helped tobacco plants to more effectively withstand stress. Abel *et al.* (2013) highlighted that additional BC application improved soil bulk density, water holding capacity, and water retention, which considerably improved plants' ability to tolerate drought. According to Lehmann *et al.* (2011), BC also improves soil WHC and aggregate stability in coarse texture soils, both of which are crucial for plant growth. Soil microbial biomass (SMB), is crucial to the breakdown of organic matter and a higher SMB increases soil fertility and nutrient availability, additionally, it acts as a linkage between the sources and sinks of soil nutrients. (Marschner *et al.,* 2015). Osmotic stress induced by drought stress results in microbial mortality and a decrease in SMB (Sanaullah *et al.,* 2011). SMB decline brought on by a drought slows OM decomposition under DS (Hailegnaw *et al.,* 2019), However, it has been demonstrated that BC increases OM, microbial activity, and nutrient levels while also improving nutrient levels in the soil, soil fertility, and plant growth (Cornelissen *et al.,* 2018).

Additionally, BC increases soil organic carbon, which improves soil enzymatic activity and microbial diversity as well as plant performance (Rahman *et al.,* 2021). DS has detrimental effects on the biological qualities of soil, however BC significantly mitigates these effects and enhances soil biochemical properties. For instance, compared to the control and lower rates of BC treatment (28 g kg^{-1}); the application of BC at the rate of 38 g kg^{-1} significantly enhanced the soil phosphorus (P: 18.72%), K (7.44%), soil carbon (11.86%), nitrogen mineralization (16.35%), and soil respiration (6.37%) (Zaheer *et al.,* 2021).

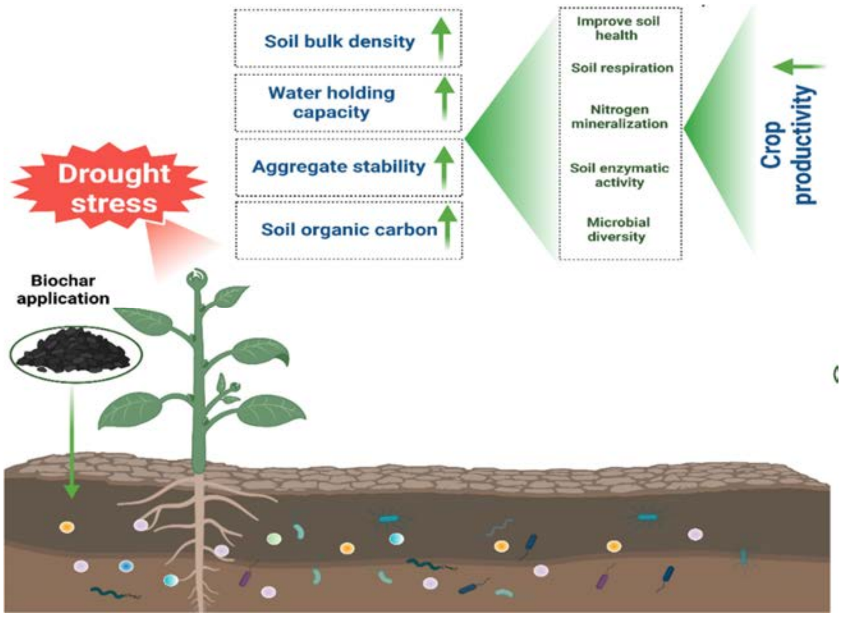

Figure 3. Biochar application improves soil bulk density, water holding capacity, aggregate stability, soil carbon contents, soil enzymatic and microbial activities and soil nutrient and water holding capacity thus ensures better plant growth under DS

Limitations of using biochar amendments

Biochar has a several applications for improving soil quality however, it also has several drawbacks (Liu *et al.,* 2019). In the wrong circumstances, biochar can cause soil compaction however, with good planning and coordinated management, these difficulties relating to the soil could be managed. Biochar contains a number of pollutants, including heavy metals, metalloids, and dioxins, which could be detrimental to the health of plants and soil (Kavitha *et al.,* 2018).

Therefore, moderate pyrolysis temperatures of less than 500 °C or good quality feedstock (with few or no pollutants) could lessen the contamination problems (Liu *et al.,* 2020). To reduce occupational health and fire threats, health and safety precautions must be taken during the manufacture, transportation, application, and storage of biochar (Xu *et al.,* 2015). The distribution of biochar pores changes the physical characteristics of soil, including aeration, habitat, and water retention. A high application of biochar can raise the pH and salt levels of the soil, which might eventually have an impact on earthworms (Shi *et al.,* 2019). There is currently limited knowledge about biochar's ability to store carbon in soils. In the future, it is anticipated that a variety of environmental, economic, and social factors will influence the soil's ability to sequester carbon after the addition of biochar (Zhang *et al.,* 2019). The handling, transportation, and storage of 23,000 tons of biomass per day by large processing facilities calls for high-capacity infrastructure (Hasnain *et al.,* 2023).

The presence of a hard cellulosic structure in feedstock can cause problems in BC production (Marousek *et al.,* 2019). Additionally, if biochar is not generated by environmental regulations, it may result in several environmental problems, including concerns with local health, excessive deforestation, and greenhouse gas emissions (McCarl *et al.,* 2009). The presence of volatile compounds in BC also affects germination and crop productivity (Pandey *et al.,* 2020; Tripathi *et al.,* 2020). During continuous pyrolysis, nutrients in biomass, namely nitrogen and sulfur, could be lost (Ndirangu *et al.,* 2019). When it comes to air quality, biochar's ash content is a source of dust particulates that, if not properly handled, can lead to respiratory illnesses. Additionally, long-term crop residue use in the formation of biochar could disrupt local nutrient cycling loops and worsen soil health in particular places where nutrient circularity is poorly managed (Ashiq and Vithanage, 2020).

Synergistic enhancement of biochar properties to induce drought stress tolerance in plants

Biochar is an imperative gold carbon to improve soil aggregation, soil water balance, nutrient and water holding capacity and reduce the erosion losses (Lee *et al.,* 2019). Compost contains appreciably amount of OM and it also substantially improve the soil properties and plant productivity (Alshankiti and Gill, 2016). Therefore, BC can be combined with compost to get better results in terms of soil fertility and quality and resistance against abiotic stresses (Canellas and Olivares, 2014; Palansooriya *et al.,* 2019). The characteristics of BC after pyrolysis can be affected by the addition of different additives (Lehmann and Joseph, 2009). According to Feng and Zhu (2018), the breakdown of lingo-cellulosic compounds by the use of iron or alkali can boost BC output. Similarly, adding phosphoric acid to the feedstock can improve the function groups, lower the pH of the soil, and have a favorable impact on the growth of the soil and plants (Peng *et al.,* 2017).

The combine use of BC and compost can have significant impact on nutrient absorption, and it also positive affect soil fertility, plant growth and soil water status (Abideen *et al.,* 2021; Antonangelo *et al.,* 2021). It is also possible to co-compose biochar with already-composted materials. For example, BC composted with iron substantially improve *Salix viminalis* (three folds) growth, soil fertility and reduced the soil acidity (Lebrun *et al.,* 2020). Similarly, *Chenopodium quinoa* plants showed an increase of 305% in yield with co-composted BC application under nutrient poor sandy soils (Kammann *et al.,* 2015). Likewise, use of peanut shells-based BC improved the yield of *Chrysanthemum coronarium* by 16%-107% and increase nutrient availability, SOM and water holding capacity (Liu *et al*., 2019). In another study application of BC and poultry manure compost increased the grain yield, leaf area and reduced the electrolyte leakage (Lashari *et al.,* 2015) and Luo *et al.* (2017) also found an increase of >20% in growth of *Sesbania canabina* plants following application of BC and compost. Humic acid is an important substance to improve soil quality and application of BC and humic acid can lead to increase in leaf water contents, osmotic potential, electron transport and photosynthesis under DS (Haider *et al.,* 2015; Zhao *et al.,* 2019).

Nano-materials are the key players to induce stress tolerance and combined application of BC and nano-materials could be an important practice to ensure better plant growth under stress conditions (Cornelis *et al.,* 2014). For instance, application of Zn nano-particles (NPs) with BC (1%) improve the maize height, leaves, dry biomass, chlorophyll synthesis and reduced the EL, MDA and H_2O_2 production (Rizwan *et al*., 2019).

Likewise, Elshayb *et al.* (2022) found that BC and combined use of Zn-NPs induced positive impact on chlorophyll contents, RWC, plant height, chlorophyll synthesis, leaf area, panicles, panicle length, grain and biomass yield. These authors suggested that combined use of Zn-NPs and BC can be an optimum practice to maximize the grain yield and WUE in rice crop (Elshayb *et al*., 2022). Phyto-hormones govern all developmental aspects in plants and they participate in cellular signaling and regulate the plant responses and adaptions against stress conditions. For instance, in maize and wheat plants melatonin and combination with BC increased the chlorophyll synthesis, photosynthetic rate and grain yield and reduce the oxidative damages (Wei *et al.,* 2015; Faraq *et al.,* 2020).

Different microbes including bacteria and AMF has shown the promising results to improve the plant growth by stimulating antioxidant activities, hormones and osmolytes accumulation, and genes expression (Jambon *et al*., 2018). The combination of BC and microbes could be an important approach to improve the plant growth and soil fertility (Ohsowski *et al.,* 2018). For instance, application of BC in combination with *Funneliformis mosseae* and *Pseudomonas* increased grain yield, nutrient uptake and root colonization in *Apium graveolens* plants (Ning *et al.,* 2019). Likewise, compost, BC and *Thiobacillus thiooxidans* promoted higher nutrient uptake in quinoa plants BC (Ramzani *et al.,* 2017). On the other hand, BC in combination with *Pseudomonas fluorescens* alleviated toxic effects of DS in cucumber and lead to a marked increase root and shoot length, biomass production, chlorophyll synthesis, RWC and membrane integrity (Nadeem *et al.,* 2017). The study findings of Hashem *et al.* (2019) showed that BC and *Conocarpus erectus* application improve drought tolerance, root and shoot growth, RWC, membrane stability, and nitrogen fixation by *Cicer arietinum*. Further in another study it was found that co-application of BC with PGPR showed a marked improvement in nutrient uptake, RWC growth traits as compared to control plants. Moreover, co-application of PGPR and BC also increased sugars, proteins, flavonoids, phenolic compounds, and DHAR, GR, POD and SOD activities as compared to control plants (Lalay *et al.,* 2022).

Conclusions

Drought stress causes a serious reduction in plant performance by disturbing plant physiological and biochemical functioning and increasing the production of ROS that damage the major molecules in plants. BC application improves plant water relations, nutrient and water uptake, photosynthesis, hormonal balance, and osmolyte accumulation and gene expression thus mitigating the adverse impacts of DS. However, the role of BC in mitigating the damaging effects of drought is not fully explored and many questions need to be answered. For example, there is no evidence about the role of BC on seed germination and it can be fascinating to explore how BC affect different mechanism involved in seed germination. Nutrient homeostasis plays an important role under DS and role of BC on nutrient uptake is poorly studied under DS, therefore, it is the need of time to underpin how BC affects nutrient channels and transporters under DS. Osmolytes and hormones play an imperative role against DS stress, and the role of BC in the accumulation of osmolytes and hormones is poorly studied. This is crucial to determine the complex relation between BC and the accumulation of different hormones and osmolytes under DS. The role of BC is mostly studied under control and more field studies are needed for the promising future of black gold.

The use of BC can reduce the harmful effects of DS however, it depends on BC application rate, feedstock type, and properties of BC. However, the performance of BC in mitigating drought stress can be increased by using BC in combination with other amendments. For instance, BC can be combined with microbes that can provide promising results to mitigate drought stress effects. Further, BC can also combine with composts, humic acid, nano-particles, and phyto-hormones to improve its performance in mitigating the adverse impacts of drought. Besides this engineered BC can be also used to mitigate the adverse impacts of drought and future research must be conducted on this aspect. The continuous supply of BC is also an important task and wise strategies must be used for biochar production and its subsequent utilization.

Authors' Contributions

Conceptualization, WH and GJ. Writing–original draft preparation, WH and GJ. Writing – review and editing, WJ, AM, AR, MUH, JMA, MIA, MNS, AAR, MIA and WFS. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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