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Addressing Abiotic Stresses and Advancing SDGs by Biochar for Sustainable Agriculture and Environmental Restoration

Abhishek Singh[1], Ragini Sharma[2], Sakshi Singh[1], Rupesh Kumar Singh[3], Athanasios Alexiou[4], Joao Ricardo Sousa[3], Hassan El-Ramady[5*], Marina Burachevskaya[6], Vishnu D. Rajput[7] and **Karen Ghazaryan[1]**

[1]*Faculty of Biology, Yerevan State University, Yerevan , Armenia*
[2]*Department of Zoology, Punjab Agricultural University Ludhiana-141004 Punjab, INDIA*
[3]*Centre for the Research and Technology of Agroenvironmental and Biological Sciences, CITAB, Inov4Agro, Universidadede Trás-os-Montes e Alto Douro, UTAD, Quinta de Prados, 5000-801 Vila Real, Portugal*
[4]*Department of Research & Development, Funogen Athens, 11741, Greece*
[5]*Soil & Water Dept., Fac. Of Agri., Kafrelsheikh Uni., , Egypt*
[6]*Laboratory of Soil Chemistry and Ecology, Faculty of Natural Sciences, Tula State Lev Tolstoy Pedagogical, University (Tolstoy University), Lenin Avenue, 125, Tula 300026, Russia*
[7]*Academy of Biology and Biotechnology, Southern Federal University, Rostov-on-Don, Russia*

GLOBAL FOOD production is declining due to land degradation and cultivation issues, influenced by various factors, such as erratic changes in the climate, growing industrial and mining sectors, pesticide usage, and a greater reliance on wastewater for farming. Biochar offers a solution to maintain agricultural productivity by mitigating the adverse effects of climate fluctuations for example drought and waterlogging conditions are deteriorated factors for soil. They can immobilize both inorganic and organic pollutants through mechanisms such as co-precipitation, ion exchange adsorption, electrostatic attraction, and surface complexation, which lower their toxicity and bioavailability to plants in contaminated soils. Biochar application enhances the capacity of cation exchange and balance the acidity of the soil, water retention, microbial activity, and soil aeration. Consequently, biochar has been widely used as an additive to alleviate biotic stress in crops. This review examines how biochar amendments can assist plants in coping with adverse conditions, including salt and drought stress, and the role of biochar in fulfilling the goals of the different SDGs set by the United Nations. On pairing with stimulants like humic acid, compost, microbes, phytohormones, and nanoparticles, biochar may enable plants to endure and even flourish in harsh environments. Overall, biochar is an economical and effective method for addressing soil degradation and nutrient deficiencies, making it particularly suitable for plant cultivation in the affected areas.

Keywords: Abiotic stress, environmental stresses, food security, agriculture, soil, biochar, SDGs.

1. Introduction

Crop yields are significantly diminished by various abiotic stressors including drought, soil salinity, heat, heavy metal contamination, and cold (Toth et al., 2018; Brevik et al., 2020). These threats are expected to intensify because of the cumulative impact of climate change and pressure from the rapidly growing human population. The current global population stands at 8 billion, with recent UN projections suggesting an increase to 8.5 billion by 2030 and potentially 9.7 billion by 2050 (Sadigov, 2022). Consequently, the agricultural sector faces a substantial challenge in adapting to environmental shifts to meet rising global food demand.

Unfortunately, a large proportion of land experiences challenging circumstances (Brevik et al., 2020; Sadigov, 2022; "The State of Food security and Nation 2020). Compared to record yields, abiotic stress can lead to an average reduction in crop production of approximately 60% (Boyer, 1982). The poleward gradient of climate extremes is becoming more pronounced, with global temperature variability patterns indicating an increased frequency of heat extremes rather than cold ones (Y. Zhang et al., 2022). Recent studies employing machine learning techniques and subnational yield data have revealed that climatic extremes may be responsible for up to

*Corresponding author e-mail: ramady2000@gmail.com
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50% of the variability in global agricultural yields (Vogel et al., 2019). This research also indicated that extreme temperatures, rather than precipitation, were most strongly associated with yield anomalies in areas with regular irrigation.

Plant growth can also be impeded by contamination from heavy metals and metalloids, which may stem from natural occurrences, such as volcanic activity, mining operations, and anthropogenic industrial processes (Khilji et al., 2022). The concentrations and absorption of these elements in plant tissues can disrupt the ionic balance within cells, alter enzymatic activities in the cytoplasm, and induce oxidative stress, resulting in cellular damage. These effects can subsequently lead to impairment of photochemical processes (Munir et al., 2022). To enhance plant productivity in challenging environments, including nutrition-deficient, contaminated, degraded, arid, or saline environments, innovative and eco-friendly technologies are required. The application of biochar is a practical, efficient, and sustainable method for reducing pollution, alleviating salinity, and optimizing soil conditions for cultivation across various soil types (Qiao et al., 2017; He et al., 2019; Murtaza et al., 2023). Biochar's potential as a tool to address water pollutants is significant because of its cost-effectiveness, beneficial physical and chemical surface properties, and the fact that the biochar's source material may contain inorganic and organic contaminants (Lehmann & Joseph, 2012). Pyrolysis produces biochar as a stable, carbon-rich, porous material similar to charcoal, which reduces volatile gases and prevents oxidation, thus extending its longevity. Unlike charcoal, in which soil microorganisms cannot decompose, biochar sequesters carbon dioxide and can store carbon for extended periods due to its resistance to breakdown (Li & Chan, 2022). The carbon sequestration capabilities of biochar stem from its physiochemical properties, including its high carbon content, thermal stability, and resistant aromatic carbon structure. Several variables related to the high carbon content of biochar contribute to its ability to sequester carbon. First, it serves as a reliable carbon storage medium in soil, absorbing and retaining carbon for prolonged durations, thereby mitigating carbon dioxide (CO_2) emissions (Li & Tasnady, 2023). An increase concern on biochar can be noticed through many publications (e.g., Abdel-Motaleb et al. 2025; Abdel-Salam et al. 2025; Abuzaid et al. 2025; Farid et al. 2025; Howladar et al. 2025).

Current research suggests that different soil types require different biochar formulations. Such tailored biochar, incorporating appropriate functional groups and symbiotic microorganisms, can contribute to meeting societal objectives, such as producing safe nutrients for use in a SDGs and circular economy and reducing greenhouse gas emissions during food production. This review sought to elucidate the advantageous effects of biochar in managing abiotic stress, with a focus on drought and salinity, ultimately contributing to enhanced soil health.

2. Biochar: Black gold and a boon for Soil

2.1 Background

Biochar, a synthetic variant of the key component in "terra petra," is recognizable by its dark hue (Xiang et al., 2020). This soil type originated from ancient Amazonian techniques that transformed sandy, unproductive soils into enduring, productive fields (Marousek et al. 2019). Characterized by its mineral and aromatic carbon-rich heterogeneous composition, biochar serves primarily as an adaptable and enduring soil supplement. It is created via pyrolysis, which involves heating biomass materials such as wood, cereals, manure, and sludge at high temperatures (approximately 300-700ºC) in an oxygen-limited environment (Fig 1) (Yeboah et al., 2020). Small-scale operations process biomass at rates of 50 to 1000 kg/h, whereas large units can handle up to 8000 kg/h (X. Yang et al., 2019). There is potential to scale up the production of high-quality biochar using cost-effective and easily comprehensible technologies, particularly in developing countries (Viega et al., 2020).

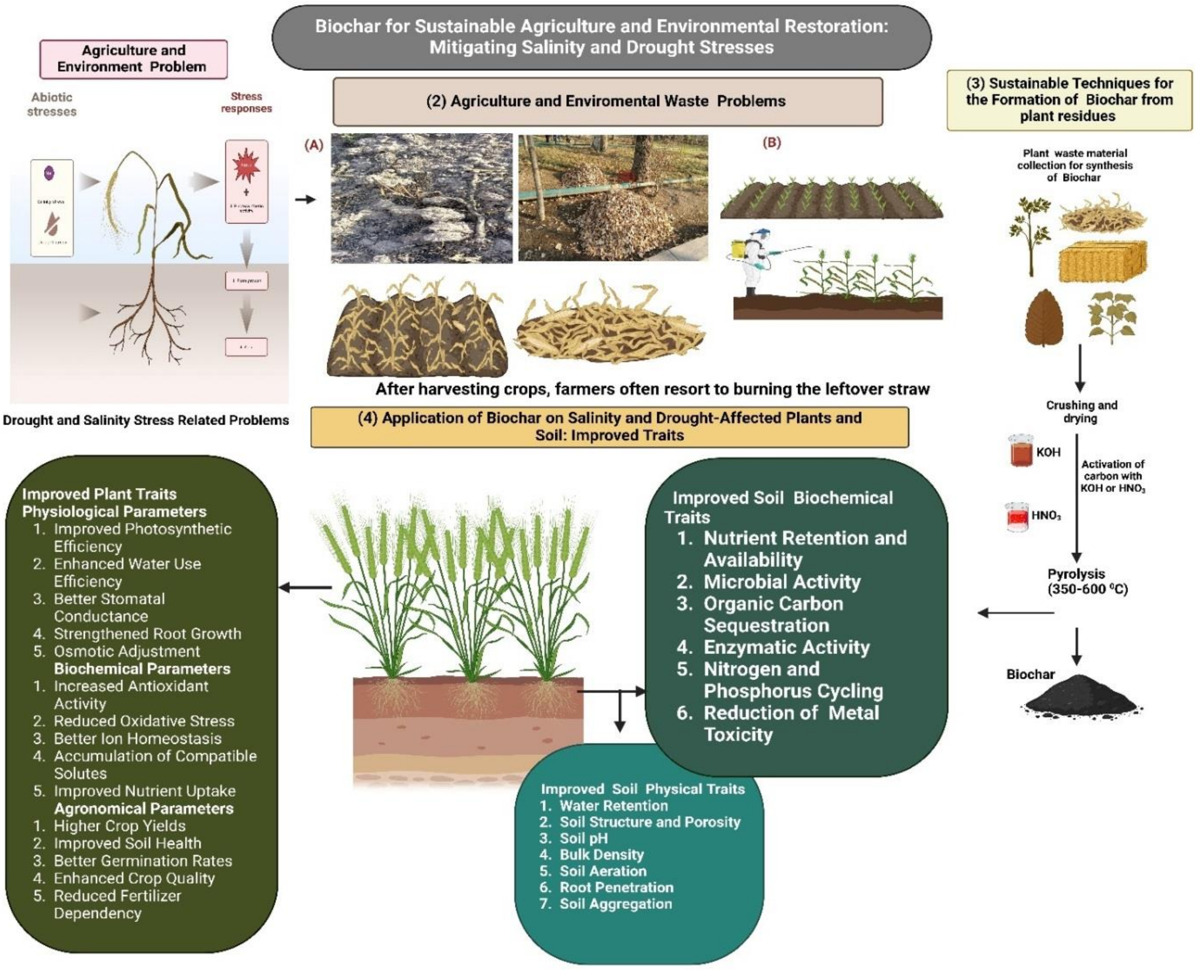

Fig. 1. Application of biochar for management of plant and soil health under salinity and drought condition.

2.2 Process of Biochar Formation

Biochar, a cost-effective adsorbent for water purification, was the focus of a study examining the viability of utilizing 600ºC to covert biowaste (such as peanut shells, sugarcane skins, and orange peels) into biochar, as an alternative to expensive woody biomass. The research employed Batch tests were used to determine the optimal duration, temperature, and quantity of water filtration. The elimination rates of ammonium ions (NH_4^+-N) were 96.3%, 74.4%, and 90.8% for peanut shells, orange peels, and sugarcane skins, respectively. Additionally, the synchronous constant index exclusion efficiencies of these materials are 26.6%, 31.0%, and 26.6%, respectively (Kwapinski et al., 2010). The most ancient method of oxidizing plant biomass involves combustion at temperatures between 400 and 700ºC with minimal or no oxygen, a process known as pyrolysis or “charring” (Mukherjee et al., 2011). Pyrolysis is a thermochemical procedure that can produce bio-oil, syngas, and biochar from biomass. On other hand, gasification involves converting biomass into various fractions by releasing gases (methane, carbon monoxide, and hydrogen) under controlled oxygen conditions (Mallick, 2019). Pyrolysis temperature, duration, and pressure influence the yield, ash content, specific pore structure, functional group quantity and type, cation exchange capacity, and surface area of biochar (Leng & Huang, 2018).

Although, carbon stability, ash, and pH increase with temperature, biochar production and acidic functional groups decline. When the residence time is set at 500-900ºC for 2 hours, the pore size and the specific surface area of the final product are likely to expand. Rather, extending this time frame over two hours may lead to porous structure collapse, resulting in a rapid reduction of specific surface area and pore area (Oni et al., 2019).

Cellulose, hemicellulose, and lignin undergo aliphatic carbon pyrolysis at low to moderate temperatures, and aromatic carbon pyrolysis at high temperatures. Between 400 and 700ºC, the biochar volatile matter, hydrogen, and oxygen contents diminished. Higher pyrolysis temperatures increase the likelihood of acid surface and aliphatic alcohol functional groups changing into fused aromatic groups that are either basic or neutral (Mukherjee et al., 2011). Consequently, the surface and chemical properties of biochar are significantly influenced by the temperature while pyrolysis.

2.3 Characteristics of Biochar

In addition to inorganic components, including potassium, silicon, magnesium, manganese, calcium, iron, and sodium, biochar is composed of hydrogen, nitrogen, and carbon, all of which contribute to its distinctive chemical attributes (K. He et al., 2020; Xu & Chen, 2013). Incorporating biochar into the soil generally results in elevated soil pH and enhanced nutrient uptake, thereby contributing to improved plant nourishment and resilience to stress (Leng et al., 2020). The biochar surface typically features functional groups, including hydroxyl, carbonyl, carboxyl, acyl, amide, aromatic, and aliphatic moieties (Y. Liu et al., 2019). These groups establish and break hydrogen bonds with protons, making them essential sites for pollutant adsorption and catalytic breakdown. Additionally, they affect the hydrophobicity or hydrophilicity, surface charge (usually negative), pH buffering capacity, and sorption intensity (A. El-Naggar et al., 2019). Free radicals are integral to the surface chemistry of biochar, although their excessive presence may adversely affect seed germination and plant development (Tang et al. 2020). The porosity of biochar, which includes nanopores (less than 0.9 nm), micropores (< 2 nm), and macropores (> 50 nm), affects its surface area. Smaller holes participate in molecular adsorption, whereas macropores are essential for soil aeration and hydrology, and encourage the presence of microbes by offering habitat niches (Trompowsky et al., 2005).

Biochar-soil interactions are significantly influenced by changes in the biochar matrix, which depend on environmental factors, soil type, and physiochemical characteristics after application. Surface functional groups on biochar are negatively correlated with saprophytic organisms, such as fungi, but are directly correlated with the type of feedstock and manufacturing circumstances (Leng, Huang, et al., 2019). In contrast to alternative organic additions, the high stability of biochar makes it an efficient enhancer with characteristics of delayed nutrient release, enhanced deteriorated soils, and maintained plant productivity during stress (Leng, Xu, et al., 2019; Trompowsky et al., 2005). The degree of aromaticity is one of the most crucial factors for the stability of biochar and is affected by the production temperature (El-Naggar et al., 2019; Leng Xu, et al., 2019; Xiang et al., 2020).

3. Role of Biochar for Abiotic Stresses Management

3.1 Drought Stress

Drought stress may significantly affect plant development and output, which affects various physiological processes (S. Kumar et al., 2018). This stress influences all stages of phenological development, from the morphological to molecular levels (Sinclair, 2011). The productivity of plants can be significantly reduced when drought stress occurs after anthesis, which affects flower formation and grain development (Pamungkas et al., 2022). It also hinders the accessibility of essential nutrients including phosphorus, potassium, and nitrogen. Water plays a vital role in transporting minerals and nutrients; however, its limited availability results in reduced transpiration rates, which further hampers nutrient absorption and utilization (Hossain et al., 2020). Additionally, drought stress has a detrimental effect on photosystems and photosynthetic pigments, leading to decreased starch production (Gahlaut et al., 2019). Cellular dehydration results in a decrease in cell size, increased protein-protein interactions, and potential toxicity, which adversely affect enzyme functionality and cytoplasmic viscosity (Anjum et al., 2011). Reduced plant development and yield can occur when insufficient water is available (Fig. 2).

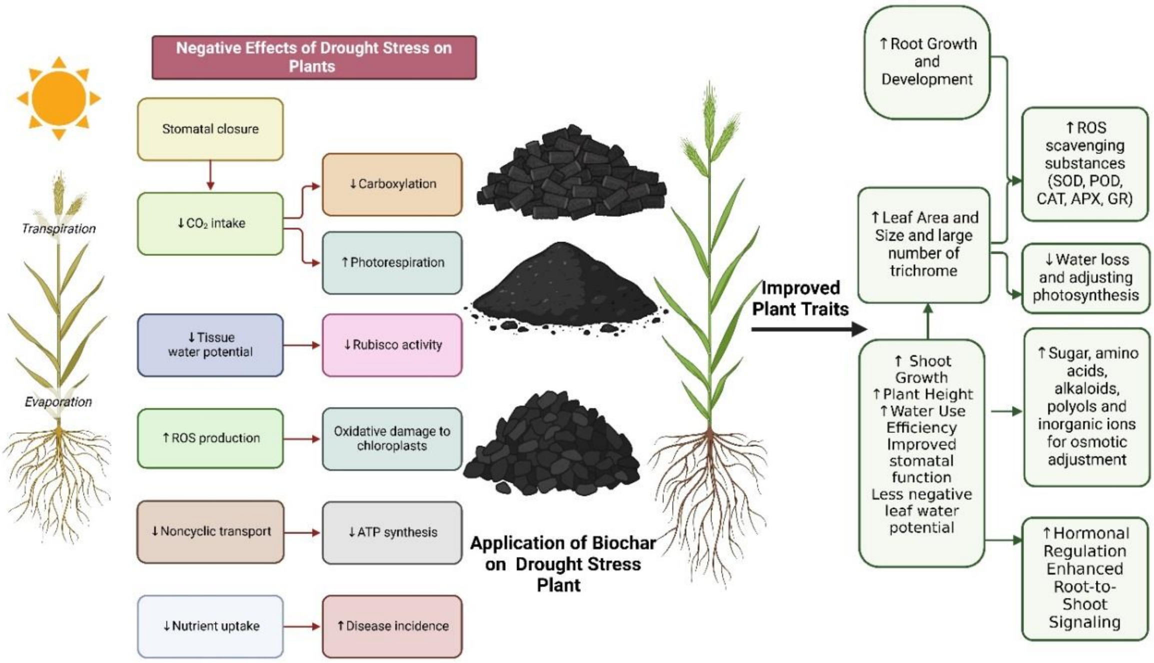

Fig. 2. Drought stress affects plants by altering their physiological and biochemical characteristics, thereby influencing their adaptation and survival under stressful conditions.

In response to water scarcity, plants close their stomata, which reduce carbon dioxide absorption and photosynthesis. In plants, which are mostly responsible for yield, drought can be observed at all phenological developmental phases from morphological to molecular concentrations. According to Cattivelli et al. (2008), numerous plant physiological processes occur under dry conditions. Although the impact of drought on production varies with its duration and intensity, the most pressing issue is drought stress following anthesis, which affects plant output irrespective of the duration or intensity of the drought (Samarah 2005). Grain yield and quality are also affected by drought stress, which limits blossom and grain filling production. Plants cannott grow without-macro-and micronutsuch asts such as potassium (K), phosphonitrogen, an; nitrogen (N); however, drought stress drastically reduces P and drwhereascally increases N, whereas it has no discernible effect on K (Farooq et al., 2009). All things considered, nutrient metabolism in cells and tissues is impaired when water is scarce because nutrients are less accessible in the root zone, less absorbed by the root hair, and less transferred in the xylem and phloem arteries (Ahmad et al., 2023c).

Transporting minerals and nutrients requires water, but when water is scarce, transpiration rates drop, resulting in less efficient nutrient uptake and utilization. Photosynthetic pigments, including carotenoids, chlorophyll a and b, and photosystems I and II, are affected by drought stress (Yadav et al., 2020). The decrease in starch synthesis is also caused by its effects on ribulose phosphatase, an enzyme involved in the Calvin cycle. Because dehydration shrinks cells, cellular substances are more pathogenic. Additionally, it causes more protein-protein interactions to clump together and denaturate. As cytoplasmic viscosity increases and solute concentrations increase, they become toxic, which influences enzyme activity, including those involved in photosynthesis (Parida and Das, 2005). Drought management and crop protection using biochar-based applications demonstrate promise in recent times (Fig 2 and Table 1).

3.1.1 Role of Biochar in Osmotic Homeostasis

Osmolytes are crucial in alleviating drought stress, although studies have indicated that DS interrupts hormonal equilibrium and osmolyte accumulation. Under stressful conditions, proline serves as both a reactive oxygen species (ROS) scavenger and an osmotic regulator. For example, DS considerably enhances proline accumulation in *M. ciliaris* leaves. However, according to Yildrim et al. (2021) which may be because BC-amended plants produce fewer ROS and experience fewer oxidative and osmotic stressors. Another study revealed that biochar combined with chitosan significantly decreased starch, sucrose, and soluble sugars in both stressed and control barley plants (Hafez et al., 2020). Gullap et al. (2022) discovered that biochar introduction and the amount of irrigation substantially influenced the GA (Gibberellic Acid) IAA (Indole-3-Acetic Acid) ABA (Abscisic Acid) content of soybean plants. Their findings showed that DS reduced IAA and GA levels and lowered ABA content in soybean plants (Gullap et al., 2022). Consequently, BC assists in maintaining hormone and osmolyte accumulation, shielding plants from the oxidative damage caused by drought, and significantly increasing drought tolerance.

Agricultural productivity is hindered by drought, which in turn impedes crop development and growth. However, there has been scant research into how biochar coating might enhance the germination of seeds and the processes behind drought (K. Zhang et al., 2024). To address this knowledge gap and elucidate the pathway of drought resistance, this study examined the protective effects of drought on the establishment and development of rice seedlings during drought. The findings of the current study revealed that biochar significantly increased plant biomass (85.7/6739%), leaf area (69.8/71.7%), plant height (19.6/10.3%), root length (33.4%), shoot length (27.4%), and emergence rate (5.5%) compared with the control.

Long-term cell growth, decreased chlorophyll degradation, and stable chloroplast structure were aided by biochar cover. During drought stress, this helped increase stomatal properties, such as stomatal density and aperture, on both the top and lower leaf surfaces. Under stressful conditions, higher photosynthetic activity and increased plant biomass are promoted by maintaining stomatal openness, which boosts photosynthetic capacity. In addition, the use of biochar preserved the integrity of the cell membrane, dramatically reduced the production of reactive oxygen species, and promoted the accumulation of osmotic protectants.

These results indicate that by carefully controlling water and nutrients, biochar coating helps plants avoid the negative impacts of drought stress on redox homeostasis, osmotic regulation, photosynthesis, stomatal aperture, and chloroplast ultrastructure. As a result, this improves the capacity of rice to tolerate drought stress and flourish. For arid reasons, the use of saline water during droughts is essential for sustainable agriculture (Murtaza et al., 2024a). Biochar, employed as a soil additive, improves soil characteristics such as the availability of plant nutrients and water retention. In greenhouse settings under drought and salt stress, the purpose of this study was to assess the impact of applying biochar on the morphological and physiological characteristics as well as the yield of *Solanum lycopersicum*. With 16 treatments spanning three variables, the experiment used a three-factorial split-plot design: (i) irrigation level (40%, 60%, 80%, and 100% of total evapotranspiration (ETC); (ii) water quality (freshwater and saltwater, with electrical conductivities of 0.9 and 2.4 dS $m^{-1,}$ respectively); and (iii) application of biochar (3% dose by weight (BC 3%) and a control (BC 0%) (Murtaza et al., 2024a). Results indicated that morphological, physiological, and yield characteristics were adversely affected by salt and water shortage, but these qualities were improved by the addition of biochar.

Drought and salt stress reduced plant height, stem diameter, leaf area, and dry and wet weight, as were the characteristics of leaf gas exchange (transpiration and photosynthetic rates, leaf gas exchange (transpiration and photosynthesis rates, leaf water content, and conductivity), particularly at 60% ETc or 40% ETc irrigation levels. Biochar application significantly improved physiological characteristics, yield, water usage efficiency, and vegetative growth factors, while reducing proline levels. The tomato yield increased by 4%, 16%, 8%, and 3% when freshwater irrigation was used at 100% ETc, 80% ETc, 60% ETc, and 40% ETc, respectively, in contrast to the control (BC 0%). In conclusion, the application of 3% biochar combined with freshwater demonstrates the potential for enhancing morpho-physiological characteristics, supporting tomato plant development, and improving yield with higher water consumption efficiency in semi-arid and arid regions. Gibberellic acid (GA3) and activated carbon biochar are examples of extremely important organic amendments (Sarwar et al., 2023). To achieve better outcomes, existing amendments must be modified over time. Therefore, in this study, potassium-enriched biochar (KBC=0.75%) was utilized as an amendment in wheat under both osmotic stress and no osmotic stress. The results demonstrated that GA3+KBC significantly increased the following traits in wheat: germination (9.44%), shoot length (29.30%), root length (21.85), shoot fresh weight (13.56%), shoot dry weight (68.33%), root fresh weight (32.68%), and root dry weight (28.79%) (Sarwar et al., 2023). Significant increases in chlorophyll, together with a reduction in wheat electrolyte leakage, further demonstrated the effectiveness of GA^{3+} KBC is the best therapy for enhancing characteristics of wheat development in the presence and absence of osmotic stress, more field-level research concentrating on different cereal crops is required.

3.1.2 Biochar based Regulation on MDA Level and Antioxidant Enzymatic Activities

Nutrient imbalances caused by drought stress significantly impair plant growth and production. Biochar is an excellent soil additive that enhances nutrient equilibrium and substantially boosts plant development. Reactive oxygen species (ROS) are produced in response to osmotic stress, which causes oxidative damage to plant cells (Fig 3) (Yadav et al., 2020). Enzymes including catalase (CAT), superoxide dismutase (SOD), and peroxidase (POD) are activated when KBC and GA3 are applied together (Sarwar et al., 2023). These enzymes are essential to maintain cellular equilibrium by eliminating ROS (Godoy et al. 2021). The observed reduction in electrolyte leakage, which indicates membrane integrity, suggests an enhanced ability of the membrane to withstand stress. Additionally, research indicates that GA3 may improve the defense systems of plants against free radicals

(Rajput et al., 2021). The accumulation of ROS in response to osmotic stress results in oxidative stress, which causes harm to plant cells (Hasanuzzaman et al., 2020). GA3 treatment increases the activity of antioxidant enzymes, shields plant cells from oxidative stress, reduces cellular damage, and improves stress tolerance (Filgueiras et al., 2020).

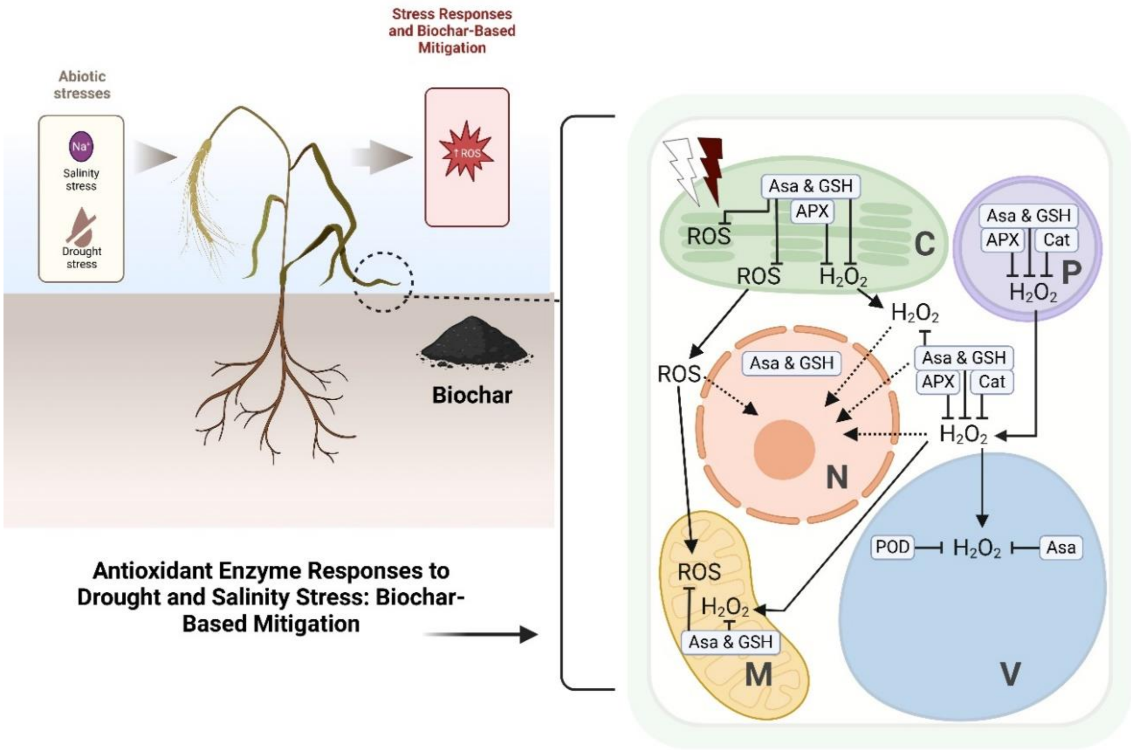

Fig. 3. The mechanism of action of biochar in mitigating drought and salinity stress involves the regulation of the antioxidant system of plants. This process aids in scavenging H_2O_2 and reducing MDA levels, ultimately enhancing plant health and increasing crop yield.

Plants can withstand osmotic stress when potassium-enriched biochar (KBC) and GA3 are combined by regulating physiological parameters such as chlorophyll content and water retention. KBC's porous structure of KBC prevents soil desiccation, promotes water availability, and reduces electrolyte leakage (Zhang et al., 2024). It also promotes soil moisture retention and preserves the cell membrane integrity. KBC controls the osmotic pressure by gradually releasing potassium ions into the soil. It reduces oxidative damage to plant cells, indirectly increasing the activity of POD, an enzyme that detoxifies reactive oxygen species (K, Zhang et al., 2024). Plant development and yield can be drastically decreased by drought stress, which affects various physiochemical mechanisms (Chang et al., 2019). It affects all phenological developmental stages from morphological to molecular concentrations. Drought stress after anthesis can significantly reduce productivity, thereby affecting flower production and grain filling. It affects the accessibility of vital nutrients such as nitrogen, potassium, and phosphorous (K. Zhang et al., 2024). Water is necessary for transporting minerals and nutrients, but its limited availability leads to decreased transpiration rates, impairing nutrient uptake and utilization. Drought stress also affects the photosystems and photosynthetic pigments, thereby reducing starch synthesis. Dehydration reduces cell size, increases protein-protein interactions, and can become toxic, negatively impacting enzyme function and cytoplasmic viscosity (K. Zhang et al., 2024).

The research findings revealed significantly elevated ROS, MDA, and electrical conductivity in plants subjected to drought conditions compared to those receiving standard water treatment (K. Zhang et al., 2024). This increase may be attributed to reduced photosynthesis, which increases the availability of electrons for ROS production. Notably, the application of the biochar coating significantly reduced drought-induced ROS production, suggesting that biochar aids in alleviating oxidative damage and consequently enhancing photosynthetic efficiency. The oxygen-containing functional groups and porous framework of the biochar particles probably increase the ability of the soil to retrain water (Suliman et al., 2017). This process helps normalize the expansion pressure and maintains plant plasma membrane stability, thereby reducing oxidative damage. Furthermore, the combined drought stress and biochar treatment increased the activity of antioxidant enzymes. These enzymes, primarily SOD, CAT, POD, and APX, are crucial for maintaining the ROS equilibrium in chloroplasts (Alharby & Fahad, 2020). In line with these observations, Hafez et al. (20200) reported that biochar treatment significantly enhanced antioxidant enzyme activity, thus reducing excessive ROS accumulation during drought stress. (Z. Khan et all., 20211) further corroborated that applications of biochar can lessen the impacts of drought stress by strengthening the antioxidant defense system, shielding drought-stressed rapeseed cell membranes from oxidative damage. Therefore, by increasing the associated antioxidant activity and improved resistance to otodative stress, biochar coating plays a critical role in maintaining ROS homeostasis.

3.2 Salinity Stress

Saline soil is a critical ecological and physiological constraint on agricultural productivity, leading to desertification and diminished crop yield (Fig 4) (Farouk et al., 2020; Sofy et al., 2020). Presently, approximately 20% of the world's irrigated land is undergoing rapid salinization, and experts project that by 2050, this issue will affect half of all cultivated areas, particularly in the most fertile regions (A. Yang et al., 2020). Salty soil degradation is predicted to occur in many regions of the world because of the use of saline water for irrigation, weakened agricultural drainage systems, and climate change (Singh et al., 2022a, b, 2023; Pandey et al., 2024). Salinity is a significant factor causing the $27.2 billion yearly losses in irrigated agriculture (Marina Voloshina, 2020; Singh et al., 2022).

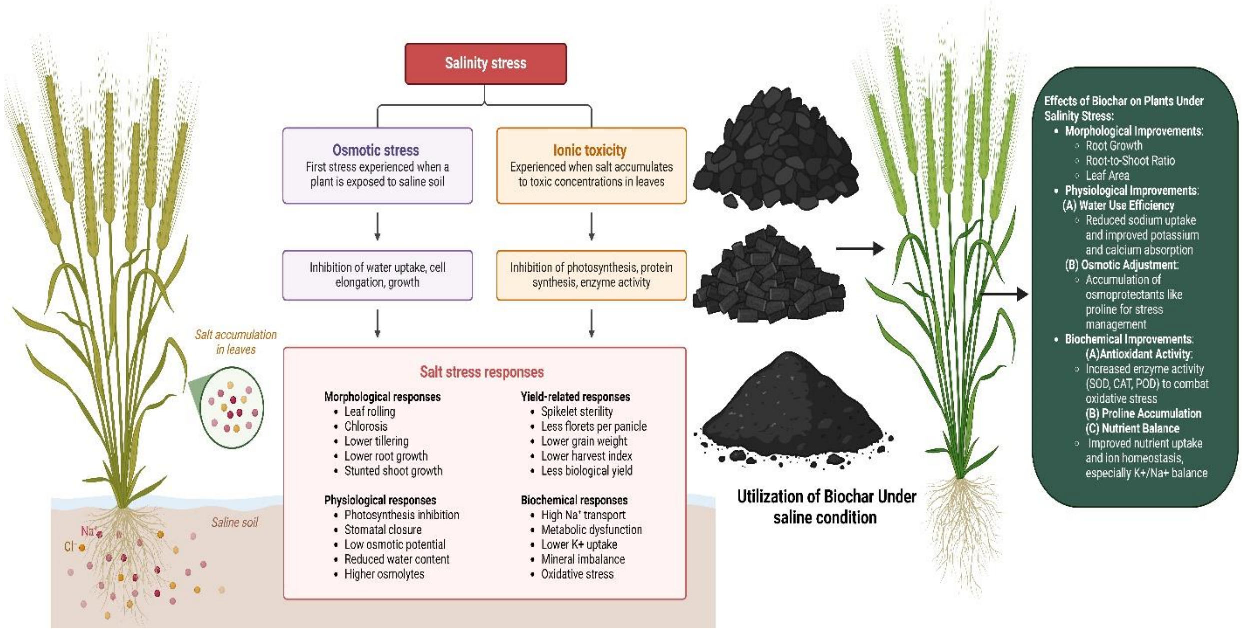

Fig. 4. The physiological and biochemical properties of plants are affected by salt stress, which influences their ability to adapt to and thrive in challenging environments.

The harmful effects of salinity stress include the inhibition of regular physiological and biochemical processes, reduced nutrient absorption, and hindered plant growth (Singh et al., 2023). It negatively affects the reactions of photosystem II (PSII) and indirectly damages molecules by generating ROS (Munns and Gilliham 2015). The disparity between ROS production and elimination leads to oxidative stress, cellular damage, and biomembrane deterioration (Razzaque et al., 2010). SOD is crucial for mitigating ROS damage by transforming superoxide anions into oxygen and hydrogen peroxide (H_2O_2) (Munns & Tester, 2008; Shahbaz & Ashraf, 2013). Subsequently, peroxidase (POD) and catalase (CAT) convert H_2O_2 into water and O_2. Simultaneously, antioxidant solutes aid in sustaining normal metabolic functions and regulating antioxidant enzyme activities, thereby improving the ability of plants to withstand stress (Kordrostami & Rabiei, 2019).

Water activity and cellular osmotic potential are reduced by organic solutes, which help to maintain turgor and related processes during periods of stress. These compounds also act as osmoprotectants, stabilizing subcellular biomembranes (Kibria et al., 2017). Plants often respond to stress bythat causes specifimolecularo-molecularmechanisms, such as osmotic adjustment (Parida & Das, 2005). Osmotic adjustment is known for its high-energy reaction that maintains cell turgor, which is beneficial for crop growth. A variety of inorganic ions and organic solutes may accumulate during the osmotic adjustment process (Bose et al., 2014; Fernando, 2020). The level of stress tolerance that is brought upon by osmoregulation can be assessed by examining the accumulation of soluble sugar, protein, and free proline in plant tissues (Atta et al., 2023; W. Wang et al., 2003). Numerous studies have examined how biochar might enhance plant performance and reduce independent salinity stress (Akhter et al., 2015a; Alsamadany et al., 2022; Hammer et al., 2015; Mehdizadeh et al., 2019; A. Yang et al., 2020). Nowadays biochar shows a potential role for reducing salinity stress-based plant morphological, physiological, and biochemical traits which help in enhancement of crop production (Fig. 4 and Table 2).

3.2.1 Salinity-Induced Ionic Stress Management Using Biochar

The growth of plants under saline conditions is influenced by the amounts of vital nutrient components in the root medium as well as by "the generalized dose-response curve." However, nutrient toxicity or deficiencies may hinder plant development below optimal levels. Competition with the main ions (Na^+ and Cl^-) reduces nutrient availability, which makes it difficult to acquire mineral nutrients under salt stress conditions, often resulting in deficiencies in Ca^{2+}, K^+, and Mg^{2+} (Fahad et al., 2014; Ghosh et al., 2016; Isayenkov & Maathuis, 2019; Mahajan & Tuteja, 2005; Miller et al., 2010). Salt stress and essential mineral elements, such as nitrogen, phosphorus, and potassium, have complicated interactions. Phosphorus is necessary for plant cellular components. Protein synthesis and water interactions depend on potassium, and plant viability depends on the sodium-potassium balance in cells.

In saline environments, plant exercise increases the Na^+ uptake, which interferes with nutrient absorption. However, the application of biochar (BC) mitigates Na^+ uptake, subsequently enhancing the absorption of other nutrients, particularly K^+ (Mansoor et al., 2021). BC addition also slightly elevates the soil electrical conductivity (EC), which facilitates the release of different nutrients by the soil (Mehdizadeh et al., 2019, 2020). Moreover, BC substitutes Na^+ in areas of soil exchange, thereby reducing Na^+ availability and improving Ca and Mg accessibility for plants (Huang et al., 2022). The high surface area, cation exchange capacity (CEC), and porosity of BC contribute to decreased Na^+ uptake. Additionally, the extensive surface area of biochar makes it an essential amendment for Na+ absorption, leading to the improved availability of beneficial nutrients (Huang et al., 2022). Additionally, BC improves K absorption and K/Na^+ ratio, two essential osmoprotectants that support improved plant development in salinized environments (Naeem et al., 2017). Consequently, BC can enhance the nutrient balance to counteract the toxic effects of salinity. It is essential to conduct comprehensive field studies on the effects of salt on soils to ascertain the influence of BC on nutrient homeostasis, as the majority of these studies were carried out in controlled environments. Akhter et al. (2015) demonstrated that potato crops exposed to 25mM NaCl salinity exhibited considerable improvement in various growth indicators when treated with 5% biochar. It has been demonstrated that biochar can reduce the effects of salt stress by reducing Na^+/K^+ ratios, which is achieved through its ability to absorb sodium ions (Na^+) while simultaneously increasing the amount of potassium (K^+) in plants (Sairam et al., 2005). Salt-affected soils exhibit deficiencies in nitrogen (N), phosphorous (P), and potassium (K^+) (Hussain et al., 2015).

Biochar is characterized by its low volatile matter and ash content, elevated pH, high mineral composition (Na^+, K^+, Mg^{2+}, Fe^{2+}), and substantial total organic carbon (TOC) levels (Qayyum et al., 2012). Adding biochar to the soil enhances the abundance of chemical elements, such as Na^+, K^+, P^+, Ca^{2+}, and Mg^{2+}. The nutrient profile of biochar, which is improved by variables such as the origin and nature of raw materials as well as the circumstances of pyrolysis (temperature, duration, aeration, and heating rate), and the specific raw material used, such as the type of wood, is mostly responsible for the increase in soil nutrient content (Ronsee et al., 2013). Moreover, the extensive surface area of biochar is associated with the availability of soil nutrients to plants (Nigussie & Kissi, 2012). Apart from its surface characteristics, such as cation and anion exchange capacity, biochar also influences nutrient release, retention, and immobilization (Butnan et al., 2015). Despite its low nitrogen content, biochar accelerates net nitrification when incorporated into the soil. Furthermore, according to Hammer et al. (2015), biochar improves the mineralization of native soil nitrogen and stimulates the growth of soil microorganisms. Our observations are consistent with those of previous studies, indicating that biochar application increases soil Ca^{2+} concentrations (Chan et al., 2008). The capacity of biochar to increase soil CEC and nutrient retention may be the cause of this, as modified soil preserves nutrients better than unamended soil (Ding et al., 2010; Jeffery et al., 2011). El-Naggar et al. (2015) observed that nutrient leaching was minimized by the generated CEC. In contrast, Brewer et al. (2012) found that, in contrast to unmodified soil, biochar increased the amount of extractable P and K^+ in the soil; our experimental results for K^+ corroborated this finding, while our P results were contradictory. Our results are in line with those of Morales et al. (2013), who found that applying large amounts of biochar reduced the available P by a small but statistically significant amount. Consequently, it is reasonable to expect that biochar will have a limited impact on the N and P status that is accessible in the soil, as demonstrated in this study.

3.2.2 The Role of Biochar in Reducing Osmotic Stress Imposed by Salinity

Osmoregulation is a well-known method used by plants to reduce the adverse effects of osmotic stress (El-Ramady et al. 2024; Singh et al. 2024; Sofo et al. 2015). Sugars, polyols, amino acids, and quaternary ammonium compounds are among the organic substances that plants collect, and they all work together to lower osmotic potential (Ozturk et al., 2021). When it comes to controlling the plant-water relationship, osmoregulation is responsible for activating defense mechanisms against antioxidant species (Cunha et al., 2016). Natural osmoprotectants are water-loving, lightweight, and positively charged (Garg and Manchanda, 2009). Compared to salt-sensitive bean types, salt-tolerant cultivars show lower protein levels but higher proline amino acid levels (Sun et al., 2007; Verbruggen & Hermans, 2008; Liang et al., 2013; Kaur & Asthir, 2015). The osmotic adjustment that occurs because of different quantities of inorganic and organic solutes differs across cultivars and species (Ashraf and Foolad, 2007a). Under salt-stress conditions, plants enhance their capacity to cope with osmotic pressure changes by synthesizing and accumulating organic osmolytes (Paul, 2013; Yi et al., 2013). Soluble sugars are crucial osmolytes for osmotic pressure regulation. When melatonin was applied to plants exposed to NaCl, fructose and sucrose levels increased noticeably. This is consistent with other studies showing that melatonin increases the amount of soluble sugars in Arabidopsis in response to salt-induced osmotic stress (H. Chen & Jiang, 2010; Yin et al., 2013). Proline, another significant osmolyte, has been extensively investigated for its function in osmotic correction (Sun et al., 2007; Kaur and Asthir, 2015). However, certain studies have proposed that elevated proline levels might be more indicative of stress-induced damage than stress tolerance (Liang et al., 2013).

Additionally, some studies have suggested that plants could benefit from reduced proline production by converting energy for the stress response, given the energy-intensive nature of proline synthesis (Verbuggen & Hermans, 2008; D. Chen et al., 2014). Some studies have revealed that while salt stress significantly increased leaf proline concentration, this increase was notably diminished with melatonin application (Ashraf & Foolad, 2007a, b, c; Bates et al., 1973; Sun et al., 2007; Abedelaziz et al., 2018; Biotechnology & 2011; Dar et al., 2015; Hnilickova et al., 2021; Hu et al., 2023;). These results support the notion that proline accumulation is more likely to be a sign of damage than a tolerance marker. Some studies have also shown that sucrose and fructose play a role in osmotic adjustment as their levels are elevated under salt stress conditions and further increase when salt stress is combined with melatonin treatment (Saxena et al., 2013; Lemmens et al., 2019; Ahanger et al., 2021). Recent studies have demonstrated that biochar reduces osmotic stress by enhancing soil moisture retention and promoting the release of mineral nutrients in plants and soil solutions. The main cause of this advantageous impact is the high adsorption capacity of biochar, which allows it to bond strongly with sodium ions. Through improved water retention and higher carbon storage, biochar lowers osmotic stress and promotes nutrient release by absorbing more sodium ions into the soil. As a result, plants show notable increases in stomatal conductance, transcription rate, and photosynthetic activity (Anwar et al., 2023). Moreover, biochar has been found to effectively lower the sodium-to-potassium ion ratio and sodium content in various plants, thereby reducing the detrimental effects of salinity on plant development (Anwar et al. 2023).

3.2.3 Methods for Antioxidants Defense System Salinity Stress Management Using Biochar

ROS produced by plants due to abiotic stress can damage various cellular molecules. To combat ROS, plants employ both enzymatic and non-enzymatic strategies, such as glutathione-synthesizing enzymes SOD, CAT, POD, APX, and GR (Fig 4) (Dioniosio-Sese & Tobita, 1998; Petridis et al., 2012). However, enhanced enzymes for scavenging reactive oxygen species are not always indicative of greater tolerance to salinity (Shah et al., 2021; Ekim et al., 2024). Factors such as the location where entioxygenic enzymes are produced, how they function, and how various antioxidant enzymes interact assist in making antioxidant systems more effective. Hydrogen peroxide (H_2O_2), the most detrimental ROS, is responsible for nearly half of the damage inflicted by oxygen radicals during photosynthesis (AbdElgawad et al., 2016; El-Badri et al., 2021).

According to recent studies, biochar can enhance carbon fixation in plants under stress conditions by improving the antioxidant activity and stabilizing photosystem II. This beneficial effect has been observed in *Phragmites karka* experiencing drought stress (Abideen et al., 2020) and in soybean subjected to salt stress (Mehmood et al., 2020). Comparable advantageous outcomes have been noted in soybean (*Glycine max* L.) when chitosan-modified biochar (CMB) was utilized, leading to improved photosynthesis and membrane stability, which also showed a correlation with the expression levels of antioxidant genes triggered by salinity. Moreover, the expression patterns of four genes that encode antioxidant enzymes (CAT, APX, POD, and SOD), as well as two genes (GmSALT3 and CHS) that provide salt resistance, were markedly increased by the use of CMB (Mehmood et al., 2020). Another finding with peas shows that biochar soil amendment has the potential to mitigate oxidative damage from salinity stress (Fareed et al., 2024).

This study evaluated the role of biochar in alleviating salinity stress in peas, using two varieties (Meteor and Green Grass) and treatments including control (0 mM), salinity (80 mM), and biochar applications (0.8 g/kg soil). Salinity stress reduced shoot and root lengths by 29% and 47%, fresh and dry weights by up to 85% and 68%, respectively, and leaf area by 71%. The photosynthetic pigments decreased by up to 76%. Salinity increased oxidative damage markers (H_2O_2 and MDA) by 79% and 89%, respectively, whereas biochar reduced these by 56% and 59%, respectively. Biochar enhanced CAT, SOD, and POD activities by up to 86% and flavonoids and anthocyanins, which are non-enzymatic antioxidants, by 67% and 112%, respectively. Up to 140% more organic osmolytes such as glycine betaine, soluble proteins, and carbohydrates. Salinity increased Na^+ uptake by 144% in shoots and 73% in roots, whereas biochar improved Ca^{2+} and K^+ uptake by up to 175% and 146%, respectively. The study concluded that 16 g/kg biochar effectively reduced salinity toxicity; decreased reactive oxygen species and Na^+ ion uptake; and enhanced pea plant development, physiology, and antioxidant activity.

Table 1. Biochar application to mitigate drought stress management.

Biochar Feedstock	Pyrolysis Temperature	Level of Stress	Experimental Crops/ Plants	Mode of Action	References
Palm fronds waste	450°C±50°C	Three deficit irrigation levels (80, 60, and 40% from ETc)	*Solanum lycopersicum* L.	Enhanced morphoo-physiological characteristic, vegetative development yield, water usage efficiency, proline content and production	(Obadi et al., 2023)
Wood and poultry manure biochars	550°C	Deficit irrigation (70% of full irrigation) & 90% of WHC	*Solanum lycopersicum* L.	By improving soil structure and field water holding capacity, biochar indirectly raises the amount of soil water available.	(W. Zhang et al., 2023)
Rice straws	500°C	Well-watered control soils, irrigated at 80 and 60% WHC	Coriander (*Coriandrum sativum);* Bengal gram (*Cicer arietinum)*	Improved soil properties, reduced arsenic pollution, and promoted plant growth, even in water scarcity-prone conditions	(A.Kumar et al., 2024)
Sesame residue	550°C	Water deficit (100, 80, 60 and 40% ETc) and control	*Solanum lycopersicum* L.	Applied combined 3% biochar increased growth yield, and water use efficiency in semi-arid and arid regions	(Murtaza et al., 2024b)
Sewage sludge and domestic wastes	250°C-550°C	Control (full-irrigated) and lowered to 50 % of the full irrigation	Cabbage *(Brassica olerecae var. capitata), cv. Yalova1,*	Improved seeding growth, photosynthetic activity, nutrient uptake, biochemical, and physiological characteristic	(Yildirim et al., 2021)

Table 2. Application of biochar for mitigation of salinity stress management.

Biochar Feedstock	Pyrolysis Temperature	Level of Stresses	Experimental Crops/ Plants	Mode of Action	References
Hard wood 80% and soft wood 20%	500°C	0, 25 and 50 mM NaCl solutions	Potato (*Solanum tuberosum* L.)	Reduced Na^+ and Na^+/K^+ ratio while raising K^+ in xylem, benefiting salinity-stressed potato plants	(Akhtar et al., 2015)
Maize straw	550°C	300 mM	Eggplant (*Solanum melongena* L.)	Through the leveling of rate photosynthesis, transpiration, stomatal conductance, and yield components	(Hannachi et al., 2023)
Maize	600°C	50 mM	Licorice (*Glycyrrhiza uralensis Fisch)*	Improved nodule formation, root architecture, and soil enzyme activity and uptake of nutrients	(Egamberdieva et al., 2021)
Rice Husk	300°C	Strongly alkaline (pH=8.87), slightly saline (EC 2.47 dS m^{-1})	Tomatoes *(Solanum lycopersicum var.* Cerasiforme)	Biochar is suggested to enhance fruit quality and increase cherry tomato output by producing bioactive compounds.	(Castaneda et al., 2020)
Rice Husk	700°C	soil salinity was 4.5 dS m-1	Rice (*Oryza sativa)*	Decreased soil ESP and enhanced the production of straw biomass	(Phuong et al., 2020)

4. Soil Fertility Improvement through Biochar: A Role with Economic Importance and Challenges

4.1 Soil Fertility Improvement

Biochar improves aeration, soil organic carbon (SOC) content, microbial biomass and function, enzymatic activity, soil water availability, holding capacity, and nutrient availability and retention (Li & Tasnady, 2023). The utilization of biochar exerts a considerable influence on soil characteristics, with outcomes varying based on the source material, pyrolysis temperature, application quantity, and soil composition. In Anthrosol soils, wheat straw biochar, pyrolysed at 350 ºC-350ºC and applied at 20-40 t ha^{-1}, led to soil pH increase of +1.2% and +8.0%, respectively (A. Zhang et al., 2010). Similarly, biochar derived from sewage sludge, pyrolyzed at 550 °C and applied to acidic soils at 50-100 g Kg^{-1}, enhanced the pH by +20.9% to +34.1%, while also substantially increasing total carbon (+554.5% to +818.2%) and total nitrogen (+350% to 550%) (S. Khan et al., 2013). Wheat straw biochar pyrolysed at 450ºC and applied at 10-40 t ha^{-1} improved both soil pH (+16.2% to +51.0%) and organic content, with effects intensifying as rates of application increased (Cui et al., 2013).

In Anthrosol soils, rice straw biochar, processed between 350-550ºC and applied at 4.5-9 t ha^{-1} elevated organic carbon (+50% to +101%) and nitrogen (+9.8% to +13.4%) levels (Zhao et al., 2014). Additional advantages have been noted for biochar derived from crop straw. When subjected to pyrolysis at 500ºC and introduced into Entisols at a rate of 16 t ha^{-1}, it enhanced soil water retention by +19.1% to +38.8% (C. Liu et al., 2016). Similarly, generic biochar processed at 400 °C and applied at 9 t ha^{-1} boosted water-holding capacity by +11% in mildly acidic soils (Karhu et al., 2011). Biochar produced from municipal biowaste, pyrolysed between 450-550ºC and applied at 40 t ha^{-1} to Anthrosol, resulted in a +20.2% increase in soil organic carbon (Bian & Rong, 2013). Nevertheless, not all outcomes were favorable; biochar from eucalyptus wood processed at low (350 °C) and high (800 °C) high temperature biochar had higher ash content than lower temperature biochar. The application of high-temperature biochar more retained ash content but have different effects on soil and crops. It is decreased Al toxicity in high-Al soil but on the other hand induced a high K level which have caused Ca and Mg deficiency in corn. The effect has greater in coarsely textured soil than in clay soils. Biochar increased Mn solubility and decreased Mn toxicity in silty-clay-loam Oxisol soil. These results highlight the process methods and need of biochar application to soil type and crop requirements (Butnan et al., 2015). Finally, biochar made from wheat straw and peanut shell was pyrolyzed at 500ºC and applied at 8 t ha^{-1} to Entisols, increasing soil organic carbon by up to +56% (A. El-Naggar et al., 2018).These results underscore the capacity of biochar to improve soil quality, although careful consideration of the application parameters is crucial to maximize benefits and minimize risks. This may be attributed to diminished plant nutrient absorption or soil C mineralization (Ippolito et al., 2020).

The inconsistent findings regarding crop yields in soils treated with biochar are likely attributable to substantial variation in both biochar properties and soil characteristics. For instance, because of its absorptive properties, biochar produced at extremely high pyrolytic temperatures (≥600ºC) may limit the absorption of nutrients by plants. The capacity of biochar to adsorb nutrients can result in a negative priming effect (PE), potentially restricting nutrient accessibility for plants, even in soils with minimal organic carbon content (Laghari et al., 2015). Consequently, any study examining the impact of biochar on soil productivity should focus on two key elements: the nutritional content of the biochar and the subsequent priming effect (PE).

4.2 Economic Importance of Biochar

The financial viability of biochar depends on its ability to generate enough additional income through improved crop yields to offset its associated costs (Galinato et al., 2011). Using biochar in farmland soils may reduce emissions and increase carbon sequestration if there is a carbon market that tracks this. This is a crucial prerequisite for promoting biochar as a technique for sequestering carbon for example, after applying biochar to the agricultural field, the farmer will benefit if the market price of biochar is less than $12,14 per metric ton (MT) and the cost of a carbon offset is $1 per metric tons of CO_2 (Galinato et al., 2011) Char application as a soil supplement (biochar) has a higher GHG-mitigation value than using char for energy (biocoal), in accordance with the Field et al. (2013) model. However, chars made using high-temperature conversion methods are more financially rewarding. Even under modest modelling assumptions, assuming ideal circumstances, the biochar scenario attains economic parity at a carbon price as low as $50/Mg CO_2 eq.

A more thorough evaluation and design optimization of biochar systems for different agricultural soils, conversion processes, and feedstocks can be achieved with the help of this model, which shows profits for farmers (Field et al., 2013). Switch grass had the highest net energy of 4899 MJ t^{-1} dry feedstock. Net greenhouse gas (GHG) emission reductions per ton of dry feedstock are- 864 kg CO_2 equivalent (CO_2e) for stover waste and –885 kg CO_2e for yard trash, with 62% to 67% of these reductions from carbon sequestration in biochar. The impact of indirect land-use change determines whether there is net GHG emission from the switchgrass biochar pyrolysis system (+36 kg CO_2e t^{-1} dry feedstock). The economic feasibility of the system using pyrolysis and biochar depends on the costs associated with pyrolysis, feedstock production, and the carbon offset value. Yard waste, which requires waste treatment and is valued at $69 per metric ton of dry feedstock when CO_2 reductions are evaluated at $80 per metric ton, has the greatest economic potential (Roberts et al., 2010). However, biochar pyrolysis systems are often not economically viable because of the long transportation distances for the feedstock. Biochar is a distributed system that uses waste biomass and may be economically feasible and beneficial for mitigating climate change.

5. Biochar and Sustainable Development Goals (SDGs)

The Sustainable Development Goals (SDGs) of the United Nations emphasize the significance of enhancing soil fertility and carbon sequestration goals for countries to accomplish by 2030 (Fig 5). These goals emphasize the critical nature of soil security through improved fertility, ensuring that plants receive adequate and balanced nutrients. To ensure soil security, sustain high agricultural yields, and strengthen rural economies, it is essential to preserve the ideal physical, chemical, and biological properties of soil (Adhikari & Hartemink, 2016). Over the past few years, there has been increasing focus on revitalizing and rehabilitating soils with low fertility and degradation. This effort aims to achieve the maximum potential production rates to satisfy the growing food needs of the world's constantly growing population (Beiyuan et al., 2016; Lal, 2015; Roberts et al., 2010).

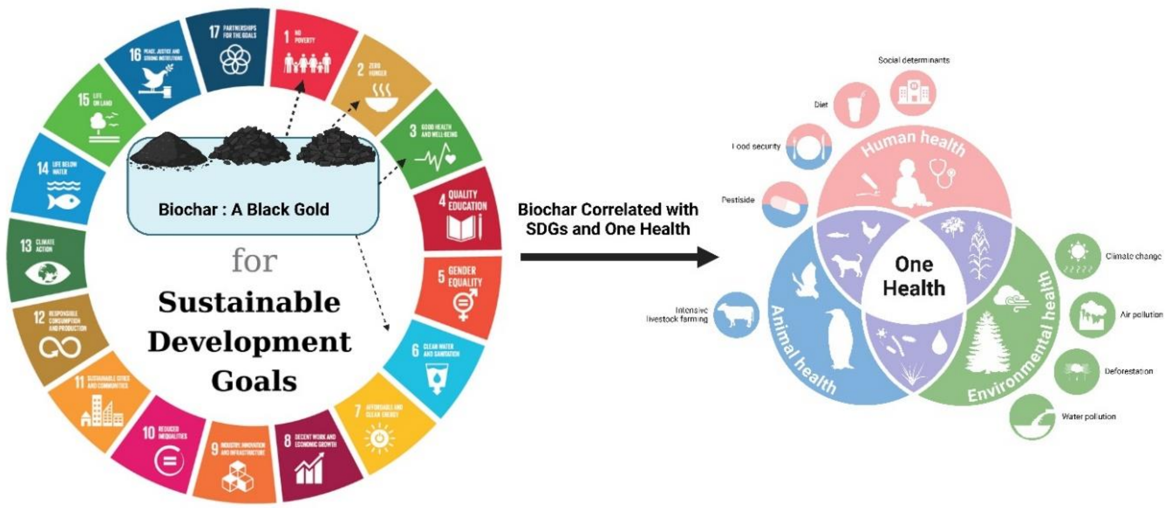

Fig. 5. The utilization of biochar enhances soil quality and agricultural yield, which are directly linked to Sustainable Development Goals (SDGs) 1,2,3 and 6. These goals are intrinsically connected to the concept of 'One Health, One Earth, which encompasses the well-being of animals, humans, and the environment.

5.1 Sustainable Developments Goals (1 and 2)

The COVID-19 pandemic has significantly impacted global efforts to eradicate extreme poverty, with the pandemic causing a rise in severe poverty in 2020. Poor nations have lagged behind in their recovery. It is becoming increasingly impossible to eradicate poverty by 2030, particularly in areas that lack financial resources to handle economic pressures. Most nations saw a return to their pre-pandemic levels of severe poverty by 2022, although low-income countries saw a slower rate of recovery. Nearly 241 million workers remain in extreme poverty, despite a steady decline in the percentage of the working population living in poverty (related SDGs 1; No poverty). Less than 30% of nations are predicted to have reduced poverty by 2030, indicating that the pandemic has probably hindered progress in reducing national poverty rates. Only 28.2% of children received child cash benefits in 2023, meaning that 1.4 billion children between the ages of 0 and 15 were uninsured.

The economic losses due to disasters have remained high, with direct economic losses exceeding $115 billion per year worldwide between 2015 and 2022. Worldwide, hunger remains a pressing issue, affecting approximately 10% of the global population in 2022, whilst 2.4 billion people suffer from moderate to severe food insecurity. Conflicts and broken supply networks caused food prices to rise significantly in approximately 60% of countries across that year. Increased efforts are required to restructure food systems with an emphasis on sustainability, resilience, and equality to reach the objective of zero hunger. Moreover, to fulfil SDG 2 (Zero Hunger) target of reducing the number of children suffering from chronic undernutrition by half, it is essential to expedite improvements in diet, nutrition, health, and hygiene.

Sustainable land management practices that incorporate biochar improve soil fertility and quality, increase revenues, and decrease input dependence, all of which contribute to alleviating poverty. Producers are incentivized to increase revenue through sustainable operations. While initiatives to alleviate poverty advance, biochar systems can help the environment by mitigating the effects of climate change. Following the realization or internalization of ecological advantages, poverty reduction can be achieved through climate change mitigation (Amin, 2023). The problem can be fixed by utilizing Biochar in sustainable land management. By effectively harnessing pyrolysis byproducts' carbon energy in biochar systems and carbon sequestration in charred material, this technique tackles climate change (Rawat et al., 2019). By reducing the impact of climate change, we can improve land management techniques, create more predictable weather patterns, and forestall potentially disastrous outcomes (Gurwick et al., 2013). Climate change mitigation, plant resistance, and soil fertility can all be enhanced by biochar. In P, K, and N, it may recover 46%, 54%, and 61% of the total additives. Burning biochar with rice straw and seed lessens the need for chemical fertilizers, increases organic matter content, and enhances rice production in temperate and subtropical countries. Applying biochar at 5 tons per hectare with chemical additives results in maximum crop yields for various crops (Converse, 2007; Maciej Serda et al., 2013; Woods et al., 2006).

5.2 Sustainable Developments Goals (3 and 6)

Global health goals face challenges in areas such as access to necessary healthcare, maternal mortality, and early deaths from serious non-communicable illnesses. The climate problem has made inequality worse, particularly for disadvantaged groups. Addressing these issues, such as inequality and environmental problems, would require significant investment and attention if SDG3 (Good health and Well-being) objectives are to be met by 2030. Protecting vulnerable populations and areas with high disease loads requires immediate action. SDG 6 (Clean Water and Sanitation) targets are not being met, with 3.5 billion people without access to sanitary facilities and 2.2 billion without clean water for consumption. Droughts devastated more than 1.4 billion people between 2002 and 2021. Severe water shortage affected 50% of the global population while 25% were impacted by acute water stress. Climate change exacerbates these issues, that puts societal stability at danger. 40% of the population of earth lives in transboundary river and lake basins, but less than one-fifth of countries have practical cooperation agreements.

Integrated water management through coordinated worldwide effort is crucial. It has been demonstrated that eating vegetables produced on soil that contains biochar, a material that eliminates toxic compounds from the soil, greatly lowers the health hazards involved. Indicators like THQ, TCR, and, and ADI are used to quantify this decrease. Biochar improves the soil's capacity to sustain life by supplying vital nutrients. By raising nutrient concentrations, lowering PTE levels, and enhancing production efficiency, it provides both direct and indirect effects (Converse, 2007; Oni et al., 2019). Biochar beneficial impact on soil extends to safeguarding water resources. The enhanced soil exhibits improved water retention capabilities and minimizes soil erosion risks. Furthermore, biochar functions as an adsorbent, eliminating contaminants from water and enhancing its quality. Consequently, this contributes to the water resource management that is sustainable. Biochar, renowned for its remarkable ability to extract various pollutants from aqueous solutions, remains an underexploited method for purifying drinking water (Ding et al., 2016). This approach may offer unique benefits in comparison to conventional cost-effective techniques (includes disinfection, sun chlorination, heating, and sand filtration). As an adsorbent that is sustainable derived from readily accessible biomaterials, biochar incurs minimal costs, making it particularly suitable for economically challenged areas (Gwenzi et al., 2017a). While existing methods primarily target disease eradication, biochar effectively removes chemical, biological, and physical contaminants. Traditional techniques, such as boiling, often produce carcinogenic by-products like chloroform. In contrast, biochar preserves the water's sensory characteristics without compromising its safety (Gwenzi et al., 2017b; X. Wang et al., 2020).

6. Conclusion

Land degradation and cultivation problems coupled with climate change impacts which connected with on industrialisation practices, mining activities, excessive use of pesticides and irrigation water. These activities are causing a serious threat to the global food production systems. Thus, the biochar could be a potential solution for these complex challenges to improve soil health. The multifaceted benefits of biochar offer binding with metals (both inorganic and organic), soil aeration, promoting microbial activity, water retention, cation exchange capacity enables potential to improve soil and plants health. Biochar also facilitates sustainable agricultural practices by ameliorating soil acidity and nutrient deficiencies, and by improving crop resistance to heat, drought, salinity, and waterlogging stresses conditions. Additionally, biochar contributes to a circular economy by turning agricultural and other organic waste into a product of economic value, fostering resource efficiency and moving away from waste generation and accumulation. This diverse use in agricultural systems offers a sustainable means of nutrient cycling and reducing agriculture detrimental effects on global environment. In combination with other stimulants like humic acid, compost, microbes, phytohormones, and nanoparticles, biochar increases its abilities to allow plants to grow in impaired conditions.

By alleviating environmental stresses and increasing agricultural yields, it also contributes to large number of SDGs agenda, particularly those connected to food security and sustainable land use, climate action, and resource conservation. In all conclusions, biochar can play a game-changer for sustainable agriculture and soil health management and could be an important element in circular economy. The sustainable and cost-effective use of biochar presents a solution to these global challenges of land degradation, food security, and efficiency in the use of resources, especially in areas of the globe that are most negatively impacted by climate change or degradation of the soil. The use of biochar therefore provides a tool for sustainable ecosystems which has the potential to promote long-term agricultural and environmental sustainability, and can be further supported with future research of, and large-scale resourcing of, biochar technologies.

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