*agriculture*

*Review*

# An Overview of Climate Change Impacts on Agriculture and Their Mitigation Strategies

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**Abstract:** In recent years, the adverse effect of climate change on soil properties in the agricultural sector has become a dreadful reality worldwide. Climate change-induced abiotic stresses such as salinity, drought and temperature fluctuations are devastating crops' physiological responses, productivity and overall yield, which is ultimately posing a serious threat to global food security and agroecosystems. The applications of chemical fertilizers and pesticides contribute towards further deterioration and rapid changes in climate. Therefore, more careful, eco-friendly and sustainable strategies are required to mitigate the impact of climate-induced damage on the agricultural sector. This paper reviews the recently reported damaging impacts of abiotic stresses on various crops, along with two emerging mitigation strategies, biochar and biostimulants, in light of recent studies focusing on combating the worsening impact of the deteriorated environment and climate change on crops' physiological responses, yields, soil properties and environment. Here, we highlighted the impact of climate change on agriculture and soil properties along with recently emerging mitigation strategies applying biochar and biostimulants, with an aim to protecting the soil, agriculture and environment.

**Keywords:** climate change; mitigation strategies; crops; biochar; biostimulants; soil

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## 1. Introduction

Climate change refers to a long-term and significant change in measures of climate such as rainfall, temperature, wind or snow patterns [1]. Global warming and greenhouse gas (GHG) emissions are considered major factors responsible for adversely accelerating the degree of climate change [2]. Due to continuously increasing anthropogenic activities, the global average temperature increased by 0.9 °C since the 19th century and it is expected to be further increased to 1.5 °C by 2050 [3]. Manifold and continuous increases in GHG emissions are highly affecting terrestrial, freshwater and marine ecosystems by causing substantial and irreversible losses [4]. These GHGs block the transmission of infrared radiations that tries to escape from the atmosphere and thus trap heat, as in a 'greenhouse' [5]. The major GHG sources include burning fossil fuels, use of nitrogen fertilizers, soil management, flooded rice fields, land conversions, burning biomass, livestock production and manure management [6]. Climate change is projected to have significant impacts on agriculture through direct and indirect effects on crops, soils, livestock and pests [7]. Though climate change is a slow process involving relatively small changes in temperature and precipitation over long periods of time, these slow changes in climate nevertheless influence various soil processes, particularly those related to soil fertility. The effects of climate change on soils are expected mainly through alterations in soil moisture conditions and increases in soil temperature and $CO_2$ levels as a consequence [8]. Global climate change is projected to have variable effects on soil processes and properties important for restoring soil fertility and productivity [9]. The major effect of climate change is expected through an elevation in $CO_2$ and increases in temperature and salinity [10].

Crop production is vulnerable to climate variability, and climate change-associated increases in temperature, increases in $CO_2$ and changing patterns of rainfall may lead to a considerable decline in crop production [3]. Changes in temperature, moisture, wet–drying and freeze–thawing cycles, etc., can lead to alterations in the growth and physiology of soil microorganisms [11]. Climate-induced changes in environmental parameters can indeed influence both the structure and function of soil microbial communities and modify, for instance, the level of interaction among microorganisms required for the degradation of organic pollutants in soil, soil organic carbon stocks, soil properties such as pH, cation exchange capacity (CEC), water holding capacity (WEC) and nutrients stock [12–14]. Also, extreme weather events such as droughts, extreme heat waves and heavy rainfall leading to floods have increased in past decades, increasing leaching, soil erosion and runoff at alarming rates. Enhancing crop production to meet rising demands owing to the increasing population, against the background of the threats of climate change, is a challenging task. Therefore, we require more attention towards adaptation and mitigation research. In the past few decades, agricultural technologies have been successful in eradicating hunger from many parts of the world, but by the virtue of chemical means and usage, which has raised more concern for environment, health and future agriculture [15]. In recent, high-input farming systems and technologies, chemical fertilizers (consisting of N, P or K) are applied excessively to provide the plant nutrient requirement for increasing the agricultural productivity worldwide [16]. The use of chemical fertilizers has caused more harm than good in long-term perspectives. Therefore, the modern agricultural sector needs more clean and green strategies for simultaneously improving crop productivity and mitigating climate change impacts.

Various terms and strategies have come forth to counter the use of agrochemicals and provide assistance in improving agriculture, such as biochar, biostimulants and bio fertilizers [17–19]. Recent advances in research have provided evidence of these strategies having potential to improve soil properties and crop yield and offset GHG emissions at significant levels. All of these strategies work on minimizing the adverse effects of climate change and act as replacement for agrochemicals. These strategies further drawn attention towards naturally occurring products to substitute the need and use of synthetic products [20–22].

In efforts to summarize the potential of biological innovations towards simultaneous increases in soil fertility, crops' productivity and environmental solutions, we highlight the unique advantages of two innovations: biochar and biostimulants. In this review, we provide an evaluation, based on what is recently known, of the potential of various biological tools such as biochar and biostimulants as a green strategy to counter the impact of climate change on atmosphere and agriculture.

## 2. Impact of Climate Change on Agriculture and Soil Properties

In the agricultural sector, fluctuations in climate, such as global rainfall, continuous rise of carbon dioxide and average temperature, have led to an increase in the frequency of extreme events that cause flood and drought disasters by posing a serious threat to global crops andcereal productivity [23,24] (Figure 1). The variation in temperature and rainfall has direct effects on the growth and maturity time of crops, due to which the crops are adversely subjected to various biotic and abiotic stresses [25]. According to a recent study, these biotic and abiotic stresses are responsible for losses of 30–50% of agricultural productivity worldwide [26]. In addition to this loss of productivity, climate change is also a threat in terms of a significant expansion in the range of pests and pathogens that could lead to an increased frequency and severity of plant diseases [27–29].

With the increase in human population and industrialization, the frequency and consequences of global warming are expected to rise, which will not be confined to any particular region but ultimately will be distributed in the global ecosystems [30]. These dangerous impacts of climate change on crop yields may compromise and risk food security worldwide [31,32]. Hence, food insecurity and climate change are also considered two major challenges of the 21st century [33].

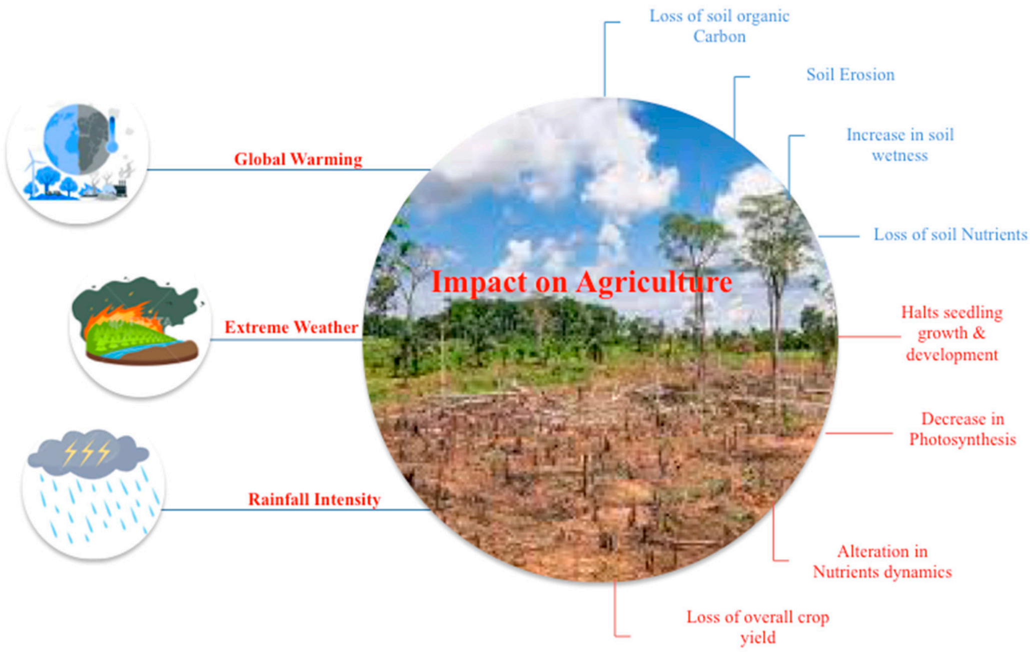


**Figure 1.** Impact of climate-induced environmental extremes on agriculture, soil and crops.

In addition to having direct effects on plants, climate change is also adversely affecting the soil systems. Fluctuations in carbon dioxide concentrations in atmosphere, rate, pattern and precipitation amounts and increasing temperature are modifying the soil–plant system by influencing the rate of decomposition and soil organic carbon levels [34,35]. The soil structure, fertility, microbial population and processes directly depend upon available organic carbon in soil [34,35].

Recent studies have shown that the combinatorial effect of temperature and moisture determine the transformation process of minerals into soil compounds [36]. Fluctuation and precipitation frequencies and seasonal temperature also affect the hydro-physical properties of soil by changing the soil water regime. Soil physical properties, such as mechanical composition or texture, structure including shape and stability, bulk density and porosity and size distribution of pores, all significantly affect the hydrological properties (hydraulic conductivity and water retention, etc.) of soil [37]. All these properties collectively contribute towards air, water and heat management of soil. These physical properties greatly influence the chemical and biological processes of soil, ultimately having a great impact on soil fertility and crop yields (Figure 2).

To uncover the degree of influence of climate change on the physical properties of soil is quite a complex process. The most common and significant direct impacts of climate on disturbing the soil structure are destructive capability of rain drops, filtering water and surface runoff and extreme events of rain [38]. Conversely, the indirect effects resulted from fluctuations in the vegetation patterns and biological properties of soil such as sensitivity of termites, earthworms and the soil microbiome to these climatic changes [39]. Soil texture, bulk density and organic matter content directly depend on climate condition [40]. Recent studies have shown that increased level of carbon dioxide in the atmosphere greatly reduces soil organic matter by increasing the soil microbial activity. Hence, it results in more carbon turnover to the atmosphere by accelerating the positive feedback in the global carbon cycle as a rise in global temperature [40]. In addition, the loss of organic matter due to soil microbial activity and soil erosion results in an increase in soil bulk density, which in turn increases the soil compaction. The soil bulk density and compaction inhibit the growth of plant roots and collectively result in poor crop yields [41].

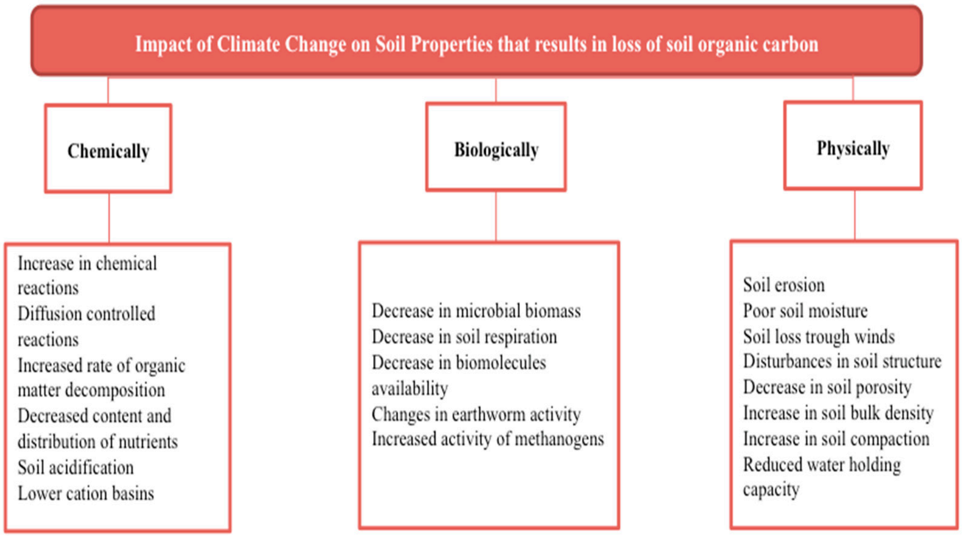


**Figure 2.** Climate extremes-associated deterioration of soil by various mechanisms [42].

Extreme climate events also affect soil chemical properties such as pH, content and distribution of soluble salts, nutrients, carbonates, cation exchange capacity and value of base saturation [43]. By increasing precipitation and rate of weathering, these phenomena lead to accelerated leaching and result in soil acidification. An acidic pH in soil facilitates the mobility of toxic heavy metals, leaving the soil depleted with basic cations [44]. Recent studies revealed that soil from more arid and warmer sites possesses lower levels of organic carbon, nitrogen and phosphorous. Soil organic matter is one of the most important factors for measuring the efficiency of soil. Biological decomposition aids in increasing the soil organic matter, and the rate of decomposition by microorganisms increases with an increase in temperature [45]. However, the increase is not a continuous process, and, after certain limits, further rises in temperature result in changes in microbial physiology by reducing carbon usage efficiency. Changes in temperature, moisture, wet–drying and freeze–thawing cycles, etc., can lead to alterations in the growth and physiology of soil microorganisms. Climate-induced changes in environmental parameters can indeed influence both the structure and function of soil microbial communities and modify, for instance, the level of interaction among microorganisms required for the degradation of organic pollutants in soil.

## 3. Crops Physiochemical Responses to Various Climate Change Parameters

Crops' growth and yield depend upon several important factors such as atmospheric temperature and $CO_2$ levels, precipitation amounts and patterns, associated salinity and the accumulation of toxins in soil [35]. With the increase in global temperature, significant changes in several hydrological parameters have been reported, such as evapotranspiration, runoff, ground water and soil moisture [46]. Most crops have quite a narrow range of survival over high temperatures (40–45 °C) [47]. It is well-known established fact that enzymes depend upon optimum temperatures to work, and failure of only a single critical enzyme system can halt the growth of crops or organisms [48]. High temperatures or heat stress is associated with various physiochemical mechanisms of crops, such as cellular injury, membrane lipids peroxidation and oxidative stress [47]. Moreover, the optimum temperature levels are different for different crops. For instance, a higher temperature (>35 °C) damages rice crops, sorghum pistils and pearl millet [49]. Similarly, a loss of wheat productivity has been observed at high temperatures. The exposure of crops to higher temperatures during different stages of development provides different results [50,51]. Recent studies reported that rice crops encountering heat stress during the grain development stage affects the crop the most. Heat stress during anthesis has been observed to inhibit pollen shed and decline in number of grains. Heat stress during reproductive stages leads to a significant loss of crop yield, as pollen and pistils are susceptible to high temperatures [52]. Crops possess various mechanisms to resist and minimize the losses of flowering such as increases in the rate of transpiration to create a cooling environment around plants [53]. However, at high temperatures, the plant prefers to use more energy for maintenance and respiration, which results in a compromise on their growth [54].

According to one estimate, with every 1 °C rise in temperature, the yield of crops can significantly reduce by 5–10% in the future [55]. Higher temperatures compel plants to complete their growth cycle in less time. This leaves plants with less time to reproduce, and ultimately results in a considerable loss in yield [56]. It is also observed that higher temperature ranges cause declines in rice yields and reproduction in beans by increasing respiration at night [57].

Increases in salinity are also a major threat to crops yield, and it has been reported to increase in coastal agriculture land, resulting from increases in sea levels during consecutive years. The water moves from the soil towards plant roots via osmosis, and this process depends upon salt levels in the soil and plants [58]. The higher soil salt levels may derive water back from plant roots towards the soil and can cause reduced productivity or even death of crop plants. Salinity also affects the uptake of nitrogen by plant roots, growth and plants' reproduction [59]. The higher temperatures and lower precipitation increase the rate of evapotranspiration in crops, which in turn results in salt accumulation on the soil surface. In this way, the underground water used for irrigation appears brackish and high in soluble salt contents, such as $Na^+$ and $Cl^-$, with lesser amounts of $Ca^{2+}$, $K^+$ and $NO^{-3}$ [60]. Hyper-ion salt stress causes oxidative damage and metabolic impairment in crops. The higher $Cl^-$ levels also affect the electrical conductivity. For some crops, levels beyond 2dsm$^{-1}$ limit their growth and yield [61]. Moreover, higher salinity and temperatures have been observed to affect the physiological responses of crops in several ways, such as by inhibiting photosynthesis and stomata closure, reducing water content and osmotic potential and triggering nutrient imbalances and osmolyte changes (Supplementary Table S1).

With increases in industrialization, urbanization, mining and use of agrochemicals, natural sources such as water and soil are consistently being polluted with heavy metals such as nickel, copper, cadmium, lead, cobalt and chromium [62]. These heavy metals are a serious threat to agroecosystems, with potentially toxic effects on crop plants. The risk of contamination of soil and the proportion of metals that cause toxicity in soil determines the active effect on the environment [63]. Climate change affects the bioavailability and mobility of heavy metals in soils. A higher average temperature increases the mobilization process and disturbs the natural environmental balance [64]. Climate change also leads to the acidification of soil, and heavy metals' toxicity worsens the acidification effect as heavy metals further decrease photosynthesis and various physiological processes in crop plants [65].

Nickel is reported to have a direct impact on the seed germination of various crop plants by affecting their enzyme activity of amylase, protease and ribonuclease. In this way, it significantly affects the digestion and transport of food resources such as carbohydrates and proteins in seeds during germination [66]. Nickel toxicity has also been reported as affecting various physiochemical processes by reducing plants' height, length of roots, biomass, chlorophyll content and leakage of electrolytes [67]. In a few crops, nickel toxicity has been reported to have an impact on chlorophyll content and accumulation of various cations such as $K^+$, $Na^+$ and $Ca^{2+}$ [68]. Lead toxicity has been observed to significantly affect various morphological and physiological processes of crops, such as halting germination, development of seedlings, elongation of roots, transpiration and growth, reducing chlorophyll, proteins and water content of plants, impairing nutrient uptake and inducing stomata closure. Lead-polluted soils are reported with inhibited seedling growth with alterations in possible mechanisms such as increases in peroxidation of lipids, superoxide dismutase and glutathione ascorbate cycle activation [69].

Copper toxicity has been reported to affect seedlings in sunflower crops by inducing the generation of reactive oxygen species and lowering the activity of catalase. Another study reported that copper toxicity halts the germination of seeds via down regulation of $\alpha$-amylase activity and affects the uptake of water, transport of food resources and overall metabolism [70]. Cadmium and cobalt also affect the seed germination process by causing delays in germination. Cadmium toxicity is associated with impaired transport of food resources and membrane damage. It is also reported to strongly affect the germination percent, growth of embryo and biomass distribution. Chromium toxicity results in reduced growth of crops, lower chlorophyll, proteins, proline content and higher metal uptake [71].

## 4. Climate Change Mitigation Strategies for Improved Agriculture

In order to emerge in modern agriculture, green strategies need to simultaneously deal with improved soil health, crops yields and climate change-associated environmental challenges. For improvements in soil fertility and plant growth, several options are available that range from traditional soil amendments to innovative solutions. Two such innovative solutions gaining immense attention are biochar and biostimulants. The unique potential of these strategies is that, in addition to enhancing soil fertility and crop yields, at the same time, these innovations have the ability to mitigate climate change impacts on agriculture and the environment.

### *4.1. Biochar*

Biochar is a solid black stable carbon material mainly composed of carbon, minerals, volatile matter and moisture [72]. For thousands of years, the pyrolysis of biomass into biofuels and biochar has presented a potential capability to sequester $CO_2$ from atmosphere, as well as to amend soils in earth layers [73]. Biochar, a porous solid material resulting from biomass carbonization in no-oxygen and low-temperature (400 °C) conditions, is considered a significant tool in the mitigation of climate change because of its role in reducing GHG emissions from soil and sequestration of carbon in more stable form of carbon materials [74]. Biochar's properties highly depend upon the pyrolysis temperature; biochar produced at high pyrolytic temperatures, such as more than 500 °C, has been reported to improve porosity and bulk density to a significant extent. Biochar produced at pyrolytic temperatures lower than 500 °C has been reported to have a higher impact on the fungal and bacterial diversity of soil. Especially in coarse textured soil, it is reported to affect bacterial diversity, whereas in fine textured soils, it affects fungal diversity more [75]. Along with several beneficial properties, the application of biochar has been reported to cause short-term negative impacts on earthworm populations. Future research efforts are required to mitigate this impact in favor of beneficial earthworm activity in soil systems [72].

Several recent studies have reported on the role of biochar in improving the efficiency of fertilizer use and thus reducing the economic and environmental burden of manufacturing given requirements of fertilizers [76–78]. The biochar-based efficient use of fertilizer can avoid the manufacturing fraction of fertilizers and associated GHG emissions [79]. Biochar-based fertilizers can increase crop productivity significantly and further increase crop productivity in soils which are not responsive to common fertilizers (Figure 3A) [80].

Biochar has a gigantic ability to sequester $CO_2$ while preventing the release of carbon back into the atmosphere after its decomposition (Figure 3B) [81]. With this practice, about 2.5 gigatons of $CO_2$ can be sequestered annually [82]. The slower decomposition of biochar in comparison to biomass stems from its potential to mitigate climate change impacts, as it lowers the rates of photo-synthetically fixed carbon returning back into the atmosphere [83]. The difference in the rates of decomposition of biochar and raw biomass critically determines the net carbon stock available in soil that has evolved over time [83]. Biochar presents larger soil carbon stocks with prolonged lifetimes in comparison to raw biomass [84]. The embedded carbon of biochar in this case is considered as a redistribution of carbon from biomass sources, with the ability to persistently derive larger carbon sequestration and influence on net GHG balances [85]. Despite several potential benefits of biochar, the applications of biochar still have some bottlenecks to be resolved. The health risks-associated with the inhalation of black carbon particles released during biochar formation is one of the health and environmental concerns that requires more research attention and management.

Biochar is composed of mixture of compounds with varying decaying kinetics in soil, and over time, the decay rates of biochar slow down [86]. Also, microorganisms cannot digest biochar completely; therefore, biochar-based amendments of soil are considered a source of permanent agents for carbon sequestration in soil [87]. Depending on the physico-chemical properties of biochar, it can offer a sustainable way towards suitable feedstock for the circular economy paradigm. The application of biochar as an enrichment of soil can offset the $CO_2$ emission of land by 12% annually. Moreover, along with performing a critical role in improving soil health and crop productivity, it has the ability to minimize 1/8 of annual $CO_2$ emissions [82]. This mitigation strategy could possibly reverse the net global warming and can significantly aid in carbon-negative technology development for the sustainable future of human civilization.

Biochar affects the rate of native soil organic matter by significantly varying the stocks of non-pyrogenic soil carbon [88]. The ways by which biochar can impact the soil organic matter includes reducing in the amounts of detritus in soil in comparison to adding biomass to soil directly [61], increasing in the yields of plants' biomass [89] and altering the rates of stabilization, humification and soil organic matter [90]. Biochar is also reported to have an impact on the improvement of crop yields via nutrient provision, alterations in the pH of soil, enhancing the cation exchange capacity (CEC) of soil, improving the efficiency of fertilizer use and enhancing the water holding capacity in the drainage of clayey or sandy soils (Figure 3) (Supplementary Table S2). Biochar application has also been reported as improving the microbe-mediated chemical reactions and enzymatic activity of soil (Figure 3C) [91]. Soil applications of biochar also have the potential to minimize soil runoff and erosion. A systematic meta-analysis revealed the mitigation of soil erosion by 16% and runoff by 25% upon biochar-based soil amendment. This effect was found to be stronger in tropical zones over subtropical [92].

Moreover, biochar also plays an important role in the mitigation of climate change impacts through several other secondary mechanisms, such as it playing a role in the reduction in nitrous oxides and methane emissions in soil. Pyrolysis of biomass to biochar can avoid processes such as decomposition and combustion of biomass, which contribute to the emission of NOx and methane in atmosphere. According to a recent study, the application of biochar could lower emissions by 50–80% in an acid savanna oxisol and by 70–80% in slightly acidic to neutral soil. Another study estimated the annual soil nitrous oxide emissions avoided by the application of biochar as a reduction factor RN of 25%. A study from China, which is a significant GHG emitter, revealed the potential of biochar to offset the total $CH_4$ and $N_2O$ emissions from China's crop land via pyrolysis of waste to biochar [93]. Biochar application, in combination with dicyandiamide, has been reported to reduce the cumulative $N_2O$ emissions by 69–70% and $CO_2$ emissions by 30–43%. This reduction in emissions was found to be associated with damage to bacterial network complexity [94]. Similarly, a few studies have reported on the reduced methane emissions of soil via the application of biochar [79]. However, further research input is required to estimate the associated reduced fraction of nitrous oxide or methane emissions in various soil conditions.

In summary, biochar has a high potential to mitigate climate change's impact on soil, agriculture, and ultimately, on crop yields. Biochar possesses more potential benefits over hazards in comparison to other soil management and mitigation technologies. However, a careful analysis is required for the production of biochar at large scale, as it could attract companies, industries and money makers to stock carbon in a stable form for trade, thereby resulting in further food insecurities. With the advent of research in this field, there is also a dire need for careful policy making, designs, protocols, project monitoring and advice for agriculture extensions to maximize the output and to avoid any negative outcomes associated with poor irrigation practices and implications.

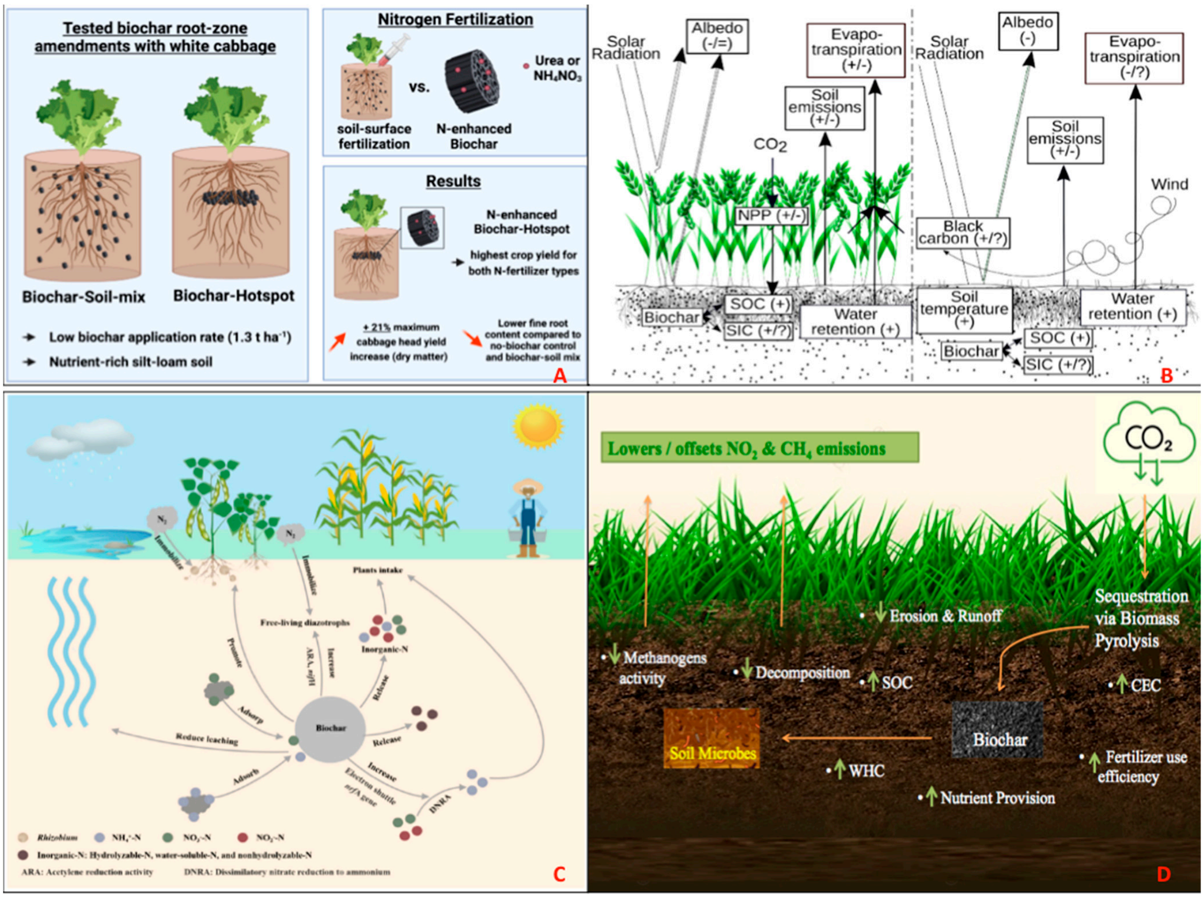


**Figure 3.** Potential role of biochar in soil amendments and crop productivity via various mechanisms; (**A**): increase in crop productivity via biochar-induced root zone amendment of crop [80], (**B**): biochar effect on climate under cultivated field by inducing positive effects on increasing soil organic carbon, soil inorganic carbon and water retention and decreasing emissions and evapotranspiration [81], (**C**): mechanism of biochar-associated improvement of soil nitrogen [91], (**D**): overall role of biochar in improving soil properties and crop productivity.

### *4.2. Biostimulants*

More recently, biostimulants have been reported as one among various significant and potential mitigation strategies in assisting plants to develop resistance against several environmental abiotic stresses resulting from rapidly changing climatic conditions [95]. Various recent studies have shown the tremendous potential of biostimulants in agriculture by providing aid to plants against climate change-induced stresses such as salinity, drought, temperature, etc. [96]. Biostimulants are one of the emerging biological strategies with potential to mitigate climate-induced biotic and abiotic stresses in plants, without compromising on soil health, plants' growth and the environment. Biostimulants are microbes, organic compounds or amalgamations of the two that could help in the regulation of plant growth and certain behaviors via alterations at the molecular, biochemical, physiological and anatomical levels [97]. Biostimulants can act as a promising mitigation strategy in recent crop production scenarios, as they are reported to function through various modes of action due to their diverse nature and the varying composition of these bioactive compounds [98]. Biostimulants can be broadly categorized into various classes such as botanical extracts including seaweed/algae extracts, amino acids, protein hydrolysates, vitamins, antioxidants, cell-free microbial products, anti-transpiration agents, chitin and fulvic and humic acid, along with their derivatives [99,100]. The application of biostimulants in very small amounts could have the potential to induce resistance against stresses, and this quality of biostimulants makes this class different from applications of fertilizers and manures to soil. Studies have also revealed their ability to contribute towards the maintenance of the ecological balance in agro-ecosystems by reducing the use of chemical fertilizers, pesticides and heavy metals in agricultural practices [101]. Based upon the immense potential of biostimulants, the European Commission has planned to substitute 30% of chemical fertilizers with organic-based inputs by the end of 2050 [95]. Along with their tremendous ability of augmentation in the levels of production, biostimulants have also been reported for their role in reducing greenhouse gas emissions by decreasing fertilizer consumption in the agricultural sector [102]. A recent study reported that extracts of seaweed can significantly reduce the release of greenhouse gases by supplementing synthetic fertilizer input in sugarcane cultivation, and observed a potential offset of 260 kg $CO_2$ equivalent/Mg cane production/ha from 5% foliar application of seaweed extract [103]. Biostimulant-induced responses differs among plant species, depending on morphological modifications to gene expression, their mode of application and phyto-hormone responses [104]. Table 1 highlights recent studies that demonstrated the extraordinary potential of biostimulants for mitigation of adverse abiotic stresses such as salinity, drought and heat or cold stress, induced by changes in climatic conditions, without compromising crop quality, productivity and production.

In summary, the use of biostimulants is an emerging mitigation green strategy that has tremendous ability to counter water scarcity or drought and soil and water salinity-associated stresses in plants, but is also a safe practice to maximize the productivity and nutritional values of crops. However, the biostimulants-associated mode of action have been frequently characterized in model studies only, and its understanding is limited under field conditions. There is significant room for research into the applications of biostimulants in cropping systems under field conditions to understand the impact of external factors on practical applications of biostimulants in agriculture.

**Table 1.** Role of biostimulants in mitigation of climate change impact and improving crops yield.

| Sr. No. | Biostimulant | Crop | Effect of Treatment on Crop | Ref. |
|---|---|---|---|---|
| 1 | *Trichoderma album* and *Bacillus megaterium* | Onion | Overall better yield, enhanced levels of potassium by 105.7%, Proline by 34%, calcium by 37% and total free amino acids by 144% after treatment with *T. album*<br>Pretreatment with *T. album* and *B. megaterium* both enhanced total carbohydrates, antioxidants, activity of superoxide dismutase, catalase, ascorbate peroxidase, glutathione-S-transferase, ascorbic acid and flavonoids | [105] |
| 2 | Silicate Compound and antagonistic bacteria *Bacillus* sp. | Banana | Treatment resulted in enhanced physiological growth performance of bananas, significantly resisted against *Fusarium* wilt disease in bananas resulting from pathogenic causative agent *Fusarium cubense*; the incidence of *Fusarium* wilt decreased by 56.25% | [106] |
| 3 | Natural organic matter-based Biostimulant | Tomatoes<br>Avocados | Plants resisted drought stress and resulted in enhanced growth of plant roots (36%) and shoots (27%)<br>Plants developed drought and salt resistance, resulting in 45% increase in yield | [107] |
| 4 | *Ascophyllum nodosum* | Watermelon | In response to salt stress, the treatment of plants with a biostimulant provoked a positive phenotypic response | [108] |
| 5 | Menadione sodium bisulfite encapsulated chitosan nanoparticles | Tomatoes | Treatment of plants with a biostimulant increased their tolerance against drought stress and delayed the need for retreatment by 1 week | [109] |
| 6 | *Ascophyllum nodosum* and zeolite | Spinach | Combined use of biostimulants resulted in significant improvement in water storage capacity of plants | [110] |
| 7 | *Yucca schidigera* extracts | Broccoli | Treatment of plants with a biostimulant resulted in strong effect of plants against drought and salt stress, also promoted germination and early vigor | [111] |
| 8 | *Chondrus crispus* extracts | Tomatoes | Treatment resulted in drought tolerance in plants along with enhanced shoot height and biomass | [112] |
| 9 | *Ascophyllum nodosum* | Tomatoes | Plants developed drought resistance by 40% in comparison to control | [113] |
| 10 | Mixture of *Ruinex*, *Penergetic*, *Azofix* | Wheat | Humus content increased, nitrogen and carbon content of soil increased, results over three years show that biostimulants resulted in promotion of mobile humic substance and mobile humic acid release. | [114] |
| 11 | *Pseudomonas fluorescens*, *Stenotrophomonas rhizopus*, *Agrobacterium rubi* | Strawberry | Treatment resulted in seven-fold increase in plant growth and fruit production; plants also developed resistance against angular leaf spot disease caused by *Xanthomonas fragariae* | [115] |
| 12 | Amino acids | Savory | Treatment resulted in enhanced dry matter yield, essential oil content, carvacrol, gamma-terpinene, alpha-terpinene and *p*-cymene | [116] |

## 5. Concluding Remarks

The uncertain climate scenario negatively impacts agriculture and is a serious cause of concern for global food security. The mitigation strategies to offset the climate-induced deleterious impact on agricultural productivity, such as biochar and biostimulants, have potential to significantly minimize the unfavorable impact without compromising environmental sustainability. Further planning and application of these mitigation strategies in an interdisciplinary approach can save the future of agroecosystems and can be used as biological tools to overcome the unpredicted impacts of climate change on agriculture. In particular, policy making towards large-scale production and health hazards due to the release of black carbon particles in air during biochar formation requires attention and needs work. Similarly, field-scale studies are required to understand the mode of action of biostimulants for their practical application in agriculture.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture13081508/s1, TableS1: Physiological and biochemical responses of plants upon abiotic stresses; Table S2: Effect of Biochar on crops and soil properties.

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