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REVIEW ARTICLE

Boosting crop productivity: The essential role of biostimulants under abiotic stress conditions

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Abstract

Climate change has witnessed detrimental effects on the environment that significantly contribute to the loss of agricultural production and productivity. With the growing population and limited or rather decreasing land for cultivation, food insecurity has become a major concern globally. Contamination of all sorts, including injudicious use of chemicals and anthropological interventions for all important reasons like ensuring food security and other short-term benefits have turned out to be the major contributors to ecosystem and soil health degradation. To balance the situation, we have credible alternatives like biostimulants- both a necessity and a sustainable option. Biostimulants are substances used or added to reduce the intensity of the harmful effects caused by abiotic stress factors like drought, salinity, temperature, heavy metal and nutritional imbalance, thereby ensuring enhanced seed germination, crop growth and development and yield. The paper discusses in detail the various potent biostimulant applications humic substances (humic and fulvic acid), chitosan, seaweed extract, protein hydrolysates and other N-containing compounds, inorganic compounds, beneficial fungi and beneficial bacteria that play important roles in increasing resilience and reducing the ill effects that plants face due to abiotic stress. Additionally, also briefing about the necessity of the current agricultural scenario to switch to such sustainable, reliable and eco-friendly options to create a healthy, habitable globe for us and future generations to thrive. Research should identify optimal biostimulant combinations for specific plants and conditions, focusing on application timing and interactions with fertilizers to enhance sustainable agriculture in the future.

Keywords

abiotic stress tolerance; biostimulant; crop growth; seed germination; yield

Introduction

Abiotic stresses related to climate change, such as drought, salinity and heat, reduce crop quantity and quality worldwide, leading to significant food, social and economic insecurity. More than 2 billion people in impoverished and developing nations lack regular access to safe, adequate and nutritious food; according to the National Nutrition Surveys report, 36.9% of the world's population is food insecure due to climate change (1, 2). Furthermore, climate change might allow some pests to spread uncontrollably, allowing them to survive the warmer winter and increase disease prevalence (3). Moreover, stomatal closure, delayed seed germination and compromised cell membrane integrity and function could all result from these unfavourable conditions affecting the plant (4).

To address the concerns of global population growth and alleviate the negative consequences of climate change-related challenges, effective strategies to increase crop yields must be implemented. Moreover, ecosystems and soil health have been further stressed by the over-dependence on chemical inputs, making it crucial to find resilient and environmentally friendly alternatives for agricultural development (5). Therefore, research on natural resources like plant extracts and biostimulants as substitutes for traditional chemical processes has been expanding recently.

This review highlights the findings of recent studies that discuss the use of biostimulants to increase resistance to abiotic stress and the ongoing anthropogenic climate change worldwide. It will delve into various types of biostimulants, highlighting their mechanisms of action and potential applications in modern agriculture.

Biostimulants

Biostimulants are substances that assist in the development of plants and seeds, but they do not fall within the category of fertilizers, pesticides or soil amendments. Typical bio-stimulants include substances that contain nitrogen, biopolymers and plant extracts (6). Many growth-promoting substances, including plant hormones, humic compounds, manure and sea kelp extracts are found in bio-stimulants (7). In general, bio-stimulants are a wide range of substances that, when applied in small amounts to plants, seeds and growing substrates, can improve physiological processes in plants that aid in growth and development or mitigate stress on plants (8). Biostimulants positively affect physiological and biochemical traits like chlorophyll content, soluble protein levels, nitrate reductase activity and root and shoot growth, leading to better growth and yield (9). European Biostimulant Industry Council (EBIC) states that biostimulants are substances and/or microorganisms when applied to plants or the rhizosphere, that stimulate natural processes to enhance/benefit nutrient uptake, nutrient use efficiency, abiotic stress tolerance, and crop quality (EBIC, 2016). “Biostimulants are defined by what they do not what they are” - Professor Patrick du Jardin, University of Liège Gembloux. These products include materials and/or microbes that, when applied to plants, can enhance physiological functions such as plant development, growth, stress tolerance, nutritional efficiency, crop quality and yield (8, 10, 11).

Comparison between Fertilizers, Hormones, Growth Regulators, Organic Matter and Biostimulants

Fertilizers provide essential nutrients for plant growth, boosting yield and productivity (12). Hormones regulate plant growth and development at the cellular level (13), while growth regulators modify plant growth patterns, such as flowering time and fruit set, by influencing hormone levels (14). Organic matter improves soil structure and fertility, promoting long-term plant health through decomposition and nutrient release (15). Whereas, biostimulants enhance growth, nutrient uptake and stress resistance by promoting physiological processes without directly supplying nutrients (8, 16). Each plays a unique role in plant growth and soil health.

Mechanism of action

***Physiological effects* :** Biostimulants are most effective in arid and desert climates, where water availability is limited, leading to significant yield improvements (17). Biostimulants enhance root development by promoting cell division and elongation, which improves root architecture and nutrient absorption under stress conditions (18). Beneficial microbes also release plant hormones like auxins and gibberellins, regulating growth and stress responses (19).

***Biochemical responses* :** Biostimulants enhance enzyme activity in the tricarboxylic acid (TCA) cycle, facilitating better carbon and nitrogen metabolism and increasing antioxidant capabilities by accumulating antioxidant substances such as phenolics, ascorbic acid and carotenoids (20). They also increase the activity of transport proteins and enzymes involved in nutrient assimilation, thereby optimizing plant nutrition and thus promoting plant resilience to abiotic stresses (18).

***Cellular mechanism* :** Biostimulants serve as priming agents, activating molecular and physiological defense systems that improve a plant's capacity to protect itself against various stresses. These alterations will remain as "primed memory," which can help plants develop trans-generational plasticity and metabolite accumulation, which can contribute to stress tolerance in future generations (21). Biostimulants interact with plants at the cellular level through various molecular mechanisms. Beneficial microbes in biostimulants colonize plant roots, forming symbiotic relationships that enhance nutrient uptake and growth. They induce systemic resistance by activating immune responses and producing defense proteins and secondary metabolites. Biostimulants improve nutrient bioavailability by solubilizing minerals, enhancing plant uptake. Additionally, they activate signaling pathways that upregulate stress-responsive genes including *COX1, bZIP1* and *Hsp20* in rice for drought tolerance; ZmPAL in maize for salinity stress; and *HSP101* in *Arabidopsis* for heat stress (22). These genes improve growth and yield by regulating protective mechanisms and metabolic adjustments. improving resilience. These complex interactions contribute to enhanced plant growth, stress tolerance and overall agricultural productivity (19).

***Types of biostimulant* :** Numerous writers have put forth various categories of biostimulants over time, depending on their source, primary ingredient or manner of action (8, 16, 23).

In the US and the EU, as well as in other countries, there is no legal or regulatory definition of plant biostimulants. Because of this circumstance, a thorough list and classification of the materials and microbes that are included in the idea are not possible. Although the source of basic components serves as the basis for the current classification, this decision does not always yield accurate information. Humic substances (humic and fulvic acid), chitosan, seaweed extract, protein hydrolysates and other N

-containing compounds, inorganic compounds, beneficial fungi and beneficial bacteria (8) are the 7 main categories into which the biostimulants are classified (Fig. 1).

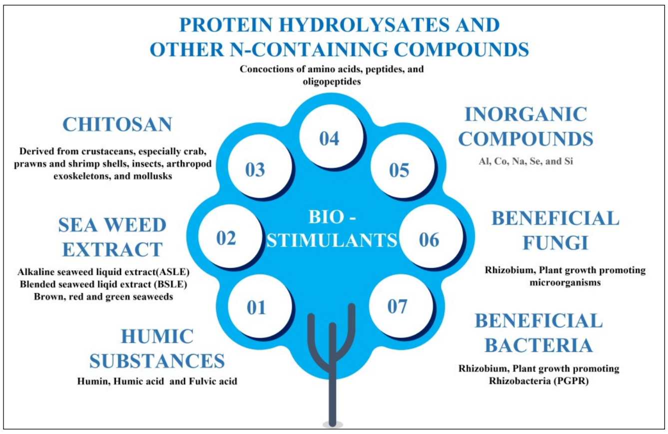

Fig. 1. Classification of biostimulants based on the source of basic components.

Humic Substances (humic and fulvic acid) as biostimulants

Humic substances : Humic substances, such as fulvic acids (FAs) and humic acids (HAs), are widely distributed and naturally occurring compounds found in soils and waters. These complicated superstructures, which are essential to the health of the soil, are formed through the breakdown of dead plant and animal materials. Their composition varies depending on where they originate and they are made up of tiny organic compounds that are weakly bonded together and have the ability to sequester minerals and release them for plant uptake (24). Humic substances, including humic acids (HA) and fulvic acids (FA), play crucial roles in enhancing plant growth and soil health. Humic acids promote root development, improve nutrient uptake by chelating micronutrients, and enhance stress resistance against abiotic factors. They also improve soil structure and increase cation exchange capacity (CEC), aiding in nutrient retention and reducing heavy metal toxicity. Fulvic acids, being more bioavailable, facilitate nutrient absorption and exhibit hormonal activities that stimulate growth (25, 26). Together, HA and FA synergistically enhance nutrient dynamics, stress tolerance and overall soil health, supporting sustainable agricultural practices (27). Humic acids (HA) and fulvic acids (FA) enhance terminal heat stress tolerance in plants by boosting antioxidant activity, inducing heat shock proteins, improving water use efficiency and facilitating nutrient uptake, thus promoting resilience against high temperatures (25).

Advantages of humic substances : Humic substances have been widely recognized as essential components in enhancing soil fertility, affecting the soil's physical, chemical, physico-chemical and biological characteristics (28). High molecular mass HS has been found to improve the activity of essential enzymes of phenylpropanoid metabolism, highlighting that HS modulates the stress response (29). Humic compounds enhance root growth, branching and hair density, which improves nutrition and water intake. The induction of lateral roots and the production of root hairs help to increase root system efficiency (30).

Seaweed extracts as biostimulant

Seaweed extracts : Biofertilizers serve a vital function in maintaining soil fertility and essential components that enable organic farming. Since seaweed functions as a biostimulant and biofertilizer, it has replaced other methods in agriculture today for promoting plant growth (31). It contains promoters, plant growth regulators, hormones and other macro- and micronutrients that stimulate faster seed germination and higher yield (32). In coastal locations, brown seaweeds are the second most common type of algae. Seaweed Liquid Fertilizer (SLF) refers to the extracts made from seaweeds.

Advantages of seaweed extracts : Seaweed extracts promote root and shoot development through natural plant hormones, enhance photosynthesis by increasing chlorophyll content and improve nutrient uptake and metabolism (33). Additionally, seaweed extracts bolster plant resilience against abiotic stresses like drought and salinity by activating antioxidant systems and delaying leaf senescence. They also enhance soil health by promoting beneficial microbial activity and improving soil structure (34, 35).

Protein hydrolysates and other N-containing compounds as biostimulant

Protein hydrolysates and other N-containing compounds : Protein hydrolysates are concoctions of amino acids, peptides and oligopeptides that develop through enzymatic, thermal or chemical hydrolysis (either acidic or alkaline). Animal and plant sources make up the majority of the protein sources in hydrolysates (36). Animal-based protein sources include vast amounts of by-products generated by poultry, livestock and fish processing industries, such as fish by-products, animal skins and furs and blood meal. Plant-based protein sources include maize wet milling and vegetable by-products (37).

Advantages of protein hydrolysates and other N-containing compounds : Protein hydrolysates (PHs) have been found to enhance nitrogen (N) metabolism and absorption in plants, which plays an essential role in regulating plant growth and development. PHs include bioactive peptides that can increase enzyme activity in plants, resulting in improved crop production, particularly under environmental stress. Protein hydrolysates can improve plant physiology by increasing photosynthesis, lignification rate, protein synthesis and mechanisms for abiotic stress tolerance. They also exhibit hormone-like action, which promotes plant growth and production. Furthermore, protein hydrolysates may minimize the demand for inorganic nitrogen fertilizers by enhancing nitrogen plant nutrition, resulting in increased plant tolerance to abiotic stresses (38).

Chitosan as biostimulant

Chitosan : Chitin is a common biopolymer found in crustaceans, insects, arthropod exoskeletons and mollusks (39). Chitosan is a cationic polymer produced by deacetylation of chitin. Chitin and chitosan enhance crop output and quality. The physiological effects of chitosan oligomers in plants are facilitated by their ability to bind a variety of cellular components, such as DNA, plasma membrane and cell wall constituents, as well as specific receptors involved in defense gene activation, like plant defense elicitors (8, 40). Chitosan promotes growth and development in various crops, including beans, potatoes, radish, gerbera, soybeans, cabbage and others (41).

***Advantage of Chitosan* :** By controlling plant metabolic reactions, chitosan can increase photosynthetic rates and improve plant resistance to abiotic stressors (42). Thus, biotransformation processes can alter a range of marine processing byproducts rich in chitin and chitosan, such as fish heads and bones, shrimp and crab shells, into bio-stimulating products (43).

Inorganic compounds as biostimulants

***Inorganic compounds* :** Beneficial elements are chemical substances that stimulate plant development and may be necessary for certain species but not all (8, 44). The five beneficial elements are Al, Na, Co, Se and Si, which are present in soils and plants as diverse inorganic salts and insoluble forms such as amorphous silica ($SiO_2.nH_2O$) in gramineous species (8). This includes cell wall rigidification, osmoregulation, minimized transpiration by crystal deposits, thermal regulation using radiation reflection, the activity of enzymes by co-factors, plant nutrition through interactions with other elements during uptake and transportation, protection from antioxidants, associations with symbionts, pathogen as well as herbivore response, heavy metal toxicity protection, plant hormone synthesis and signaling (44). Therefore, the definition of beneficial elements must take into account more than just their chemical makeup; it must also take into account specific situations in which beneficial effects on plant growth and stress response (23). Beneficial elements aid in plant resilience to abiotic and biotic stresses, offering prospects for crop management (45).

Beneficial elements such as cobalt, selenium, sodium and silicon enhance plant growth under abiotic stress conditions by increasing phytohormone crosstalk and plant -microbe interaction. The introduction of beneficial elements to stressed plants is a sustainable approach to the establishment of abiotic stress-resistant plants (45).

***Advantages of inorganic compounds* :** Beneficial elements can help crops flourish by increasing resilience to biotic and abiotic stressors. They can promote plant health, increase stress tolerance and potentially increase crop yields. Understanding and using these ingredients at low levels can result in increased crop output and nutritional value, which is critical for solving global food security issues. These elements can also promote plant metabolism, photosynthesis and the buildup of bioactive molecules, ultimately leading to improved crop production and yield (46, 47).

Beneficial fungi as biostimulants

***Beneficial fungi* :** Fungi interact with plant roots in a variety of ways, ranging from mutualistic symbioses to parasites (8, 48). Mycorrhizal fungi are a diverse group of organisms that establish symbiotic relationships with about 90% of all species of plants. Fungal endophytes are beneficial to plants because they create bioactive compounds that promote plant growth and aid in immune or adaptive responses (49).

***Advantages of beneficial fungi* :** Fungi, particularly Arbuscular Mycorrhizal Fungi (AMF), play an important role in promoting plant development by improving nutrient uptake, particularly phosphorus absorption, in low-phosphorus soils. Mycorrhizas and other fungal connections not only promote plant growth but also raise biomass accumulation and yields in a variety of crops, including legumes like chickpeas and soybeans. Furthermore, fungi assist plants in dealing with abiotic stresses such as heavy metal contamination by improving detoxifying mechanisms and increasing stress tolerance, hence adding to overall plant health and production (50).

Beneficial bacteria as biostimulants

***Beneficial bacteria* :** In terms of agricultural biostimulants, 2 major categories should be examined within this taxonomic, functional and ecological diversity: (i) mutualistic *Rhizobium* endosymbionts and (ii) mutualistic, rhizospheric PGPRs ('plant growth-promoting rhizobacteria'). *Rhizobium* and related taxa are marketed as biofertilizers or microbial inoculants that help plants absorb nutrients (8). Mutualistic *Rhizobium* endosymbionts facilitate nitrogen fixation, promote osmotic stress mitigation by synthesizing protective osmolytes, manage reactive oxygen species (ROS), enhance antioxidant activity, improve nutrient uptake and trigger physiological adaptations, all of which are vital for plant survival in harsh environments (51). PGPR is an effective tool for the development of sustainable agricultural methods because of its capacity to either directly or indirectly stimulate plant growth by inhibiting phytopathogens (52). Numerous bacterial taxa are members of the PGPR family, including *Serratia, Azospirillum, Azotobacter, Bradyrhizobium, Bacillus, Burkholderia, Enterobacter, Pantoea, Pseudomonas* and *Rhizobium* (53).

***Advantages of beneficial bacteria* :** Beneficial bacteria can promote plant growth through a variety of processes, including biological nitrogen fixation, phosphate solubilization, abiotic stress reduction, phytohormone synthesis and systemic resistance development. The potential advantages of PGPB in promoting plant development are massive, resulting in higher agricultural output and nutrient efficiency. The global market for bio-inoculants, including PGPB, is expected to expand at a pace of around 10% per year due to its positive influence on agriculture (54).

***Biostimulants in overcoming abiotic stress* :** Abiotic stress is the detrimental effect of non-living forces on living organisms in a given environment. Drought, severe temperatures (both hot and cold), salinity, heavy metals and radiation are all examples of environmental factors that negatively affect plant growth, development and productivity. The physiological and biochemical properties of a plant may be altered by these stressors, which frequently sets off stress response systems meant to help the plant survive and adapt. To maintain crop resilience and food security in the face of changing climatic conditions, agriculture must comprehend and mitigate abiotic stress (55). One of the biggest problems facing agriculture is managing abiotic stress. There is ample evidence that stress-related issues are becoming more prevalent around the globe, with the poorest nations frequently experiencing the worst effects. Abiotic stress can permanently restrict crop choice and agricultural output across wide regions and extreme occurrences can result in crop failures. Abiotic stressors harm national economies, food security and the standard of living for individual farmers and their families (56).

Abiotic factors including salt, drought and extreme heat are responsible for significant crop losses worldwide (57). Biostimulants are being added to production systems more frequently to stop these losses. The idea is to alter plant physiological processes to maximize productivity (16). The efficacy of biostimulants is maximized under stress conditions (58). So, the application of biostimulants is the environmentally sound sustainable approach to reducing the negative effects of stress conditions.

Biostimulants in overcoming drought stress

***Drought stress* :** Drought stress is characterized as a state that results from extended periods of inadequate water availability, leading to detrimental effects on the physiological functions, development and production of plants. It is a significant abiotic stressor that damages plants by depriving them of water, which causes stomatal closure, decreased photosynthesis and changed metabolic processes. Reduced crop production and weakened plant health are possible outcomes of these consequences (59). Drought stress can alter plant physiological, biochemical and molecular parameters, resulting in decreased growth, productivity and quality. Accordingly, depending on the severity and length of the stress, a crop's yield drop ranged from 13 to 94% (10).

***Role of biostimulants under drought stress* :** When plants' natural defense systems are insufficient, biostimulants are useful instruments for enhancing tolerance to drought stress (10). Applying biostimulants under mild and severe drought stress not only changed quantitative profiles in amino acid, phytohormone, flavonoid and phenolic acid levels, but it also affected gene expression and global DNA methylation patterns in plants treated with the biostimulant, leading to drought stress tolerance (60). The rhizosheath microbiome contributes significantly to plant drought tolerance by strengthening the root system, creating a suitable environment for microorganisms and boosting water-holding capacity. Plant growth-promoting bacteria (PGPB) improve drought tolerance by generating osmolytes, mimicking plant osmolytes and stimulating plant development (61) (Fig. 2).

***Seed treatment* :** Seed priming with *Bacillus subtilis* 10-4 has been shown to improve water retention in leaves and influence photosynthetic pigment accumulation. In some wheat varieties, it also lowers proline buildup brought on by dryness. These results suggest that *B. subtilis* 10-4 can be an environmentally benign treatment that enhances drought resistance and wheat development (62) (Table 1). Maize Grain Extract (MGE) has an important role in improving drought tolerance in wheat plants. Seed priming with MGE enhances proline metabolism, lowers oxidative damage and increases antioxidant enzyme activity, all of which assist plants to withstand drought stress. Furthermore, MGE has significant concentrations of phytohormones, such as cytokinins and antioxidants that enhance plant antioxidant status and reduce the impacts of oxidative stress, hence enhancing drought tolerance in wheat (63) (Table 1).

***Soil application* :** Silicon treatment in buckwheat enhances drought tolerance by enhancing root hydraulic conductivity and antioxidant enzyme activity. This increases resilience to drought conditions, making silicon an important resource for enhancing buckwheat growth and production in water-stressed situations (46) (Table 1). Soil application of *Bacillus spp.* enhances drought tolerance by promoting the synthesis of antioxidant enzymes in plants, such as glutathione reductase (GR), peroxidase (POD), ascorbate peroxidase (APX), catalase (CAT) and superoxide dismutase (SOD) (64).

***Foliar application* :** Foliar application of mushroom and crustacean chitosan reduces drought stress in tomatoes by enhancing plant tolerance via a variety of mechanisms. They raise leaf relative water content (RWC) and osmolyte levels, hence alleviating the negative effects of water deprivation. These chitosan sources also improve fruit quality, decrease lipid peroxidation and increase osmoprotectants like proline and sucrose. Moreover, they have a beneficial effect on the chlorophyll content, photosynthetic pattern and physiological water status of tomato plants under drought stress, which eventually increases plant productivity and resilience (65) (Table 1). Foliar application of F4.3S product (a novel biostimulant that contains compounds such as ascorbate, allantoin, salicylic acid, amino acids such as glycine, glutamate and proline and sources of Se, Mo and Co) alleviates drought stress in zucchini plants by improving photosynthetic activity and improving water use efficiency (WUE) once the stress circumstances are over. It reduces the production of reactive oxygen species (ROS), delays complete stomata closure and enhances the plant's ability to recover from stress. When F4.3S is applied, protective substances like proline and carotenoids accumulate faster, which helps the plants develop and become more tolerant of drought stress (66) (Table 1). Foliar application of humic acid improved the growth and leaf area index of Stevia (*Stevia rebaudiana* Bertoni) enhancing stevioside quality and mitigating drought stress impacts (67) (Table 1).

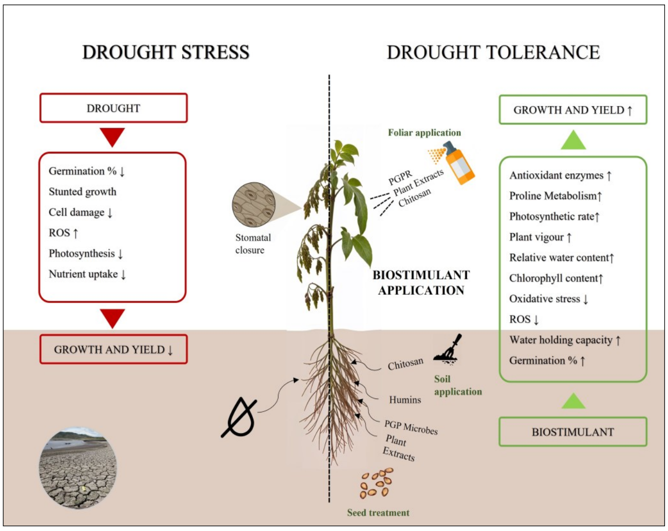

Fig. 2. Impact of drought stress and biostimulants' effect on plants against drought stress (ROS-Reactive Oxygen Species, ↑-Increase, ↓-Decrease).

Table 1. Survival mechanism in plants against drought stress using variable biostimulants

Sl. No.	Crop	Biostimulant	Mechanism of action	Reference
1.	Wheat	*B. subtilis* 10-4	Improves water retention in leaves Increases the accumulation of photosynthetic pigment	(62)
2.	Wheat	Maize Grain Extract (MGE)	Enhance proline metabolism Lowers oxidative damage Increases antioxidant enzyme activity	(63)
3.	Buckwheat	Silicon	Enhances root hydraulic conductivity and antioxidant enzyme activity	(46)
4.	Tomato	Mushroom and crustacean chitosan	Raises leaf relative water content (RWC) and osmolyte level Decreases lipid peroxidation Increases osmoprotectants like proline and sucrose	(65)
5.	Zucchini- Summer squash	F4.3S product	Improves photosynthetic activity and water use efficiency (WUE) Fastens the accumulation of protective substances like proline and carotenoids	(66)
6.	Stevia (*S. rebaudiana*	Humic acid	Improves growth and leaf area index	(67)

Biostimulants in overcoming salinity stress

Salinity stress : Salinity stress is defined as the negative effects on plants induced by high levels of soluble salts in the soil or water, which cause osmotic stress, ion toxicity and nutritional imbalance. In addition to affecting growth and development and disrupting plant water intake, this stress situation can also lower photosynthetic efficiency, which will ultimately affect crop yields and quality. A major problem in agriculture is salinity stress, particularly in dry and semi-arid areas where irrigation techniques can cause salt buildup (68).

Role of biostimulant under salinity stress : Seed treatment and foliar spray of algal extracts dramatically increased seed germination and plant growth in tomatoes under saline stress (69). Plant growth-promoting bacteria (PGPB) produce ACC deaminase, which lowers ethylene levels and reduces the detrimental effects of ethylene on root growth, hence alleviating salt stress in plants. Additionally, they improve ion homeostasis in salinized environments by increasing potassium absorption and reducing sodium buildup, which raises the K^+/Na^+ ratio. Furthermore, PGPB strengthens plants' defense mechanisms against oxidative stress caused by salt stress (70) (Fig. 3). Phosphate Solubilizing Bacteria (PSB) enhance nutrient availability, improve growth traits and increase salt tolerance in barley, aiding in coping with salinity stress (71).

Seed treatment : Pre-sowing seed treatment with *B. subtilis* 10-4 helps plants cope with salt stress in wheat. It inhibits stress -induced proline and malondialdehyde buildup, enhances water storage capacity in leaves and decreases statolite starch hydrolysis in roots. It also affects the amounts of salicylic acid, which aids in the defensive mechanisms that protect plants from the harmful effects of salt stress and promote plant growth in wheat (72) (Table 2). Maize Grain Extract (MGE) plays a significant role in enhancing salinity tolerance in wheat plants. Seed priming with MGE improves the plant's resistance to salinity stress by increasing antioxidant enzyme activity, decreasing oxidative damage and stimulating proline metabolism. Furthermore, MGE has significant concentrations of phytohormones and antioxidants, including cytokinins, which help to enhance plant antioxidant status and reduce the impacts of oxidative stress, thus enhancing wheat's ability to withstand salinity (63) (Table 2). Seed priming with 0.75% chitosan significantly improved the physiological and biochemical traits of soybeans under salinity stress, enhancing growth, enzyme activity and stress tolerance (73) (Table 2).

Soil application : Soil application of *Bacillus* spp. has the potential to adapt to high salinity environments and can reduce stress in crops like wheat, maize, chickpea and rice by generating phytohormones, ACC deaminase and enabling nutrient availability. *Bacillus* spp. can enhance plants' K^+/Na^+ ratio, which is essential for their ability to withstand salinity. They generate volatile organic compounds (VOCs), which help in reducing salt accumulation in plants (64) (Table 3). *Iyengaria stellata* and *Colpomenia sinuosa* alleviate salt stress in maize by increasing growth indices, chlorophyll and carotenoids while decreasing electrolyte leakage when applied to the soil. These seaweeds promote optimum leaf metabolism for growth resistance in saline-stress situations by enhancing nutrient uptake, particularly Na^+ and K^+, which are essential for osmotic balance and ion homeostasis. In salt-affected areas, their use as biostimulants provides a sustainable method of growing climate-resilient maize (74) (Table 3). The application of HA as soil amendments significantly improved soil nutrient availability (N, P, K, Ca, Mg and micronutrients) and enhanced microbial activity in Mexican lime trees (75) (Table 3).

Foliar application : Under salinity stress, foliar application of animal protein hydrolysate (Delfan Plus; Tradecorp International) increased capsaicin synthase and phenylalanine ammonia-lyase activity in pepper (*Capsicum annuum* L.) plants. Additionally, compared to untreated plants, those treated with biostimulants had lower peroxidase activity (76) (Table 4). Foliar application of chitosan 0.2 g/L, along with 50 mM NaCl, significantly increased the yield and quality of essential oil in savory (*Satureja hortensis* L.) plants under salt-stress conditions. The yield and quality of essential oil in savory plants were enhanced as a result of this treatment, which reduced the negative impact of salt stress on essential oil composition and production (77) (Table 4).

Biostimulants in Overcoming Temperature Stress

Temperature stress : Extreme temperatures affect the growth and development of plants (high and low temperatures). Plants respond to low or high-temperature stress based on intensity, duration and plant species. Generally, temperature changes inhibit plant growth and development (78). Heat stress in plants can be defined as the negative influence on plant growth and development induced by extended exposure to temperatures that are

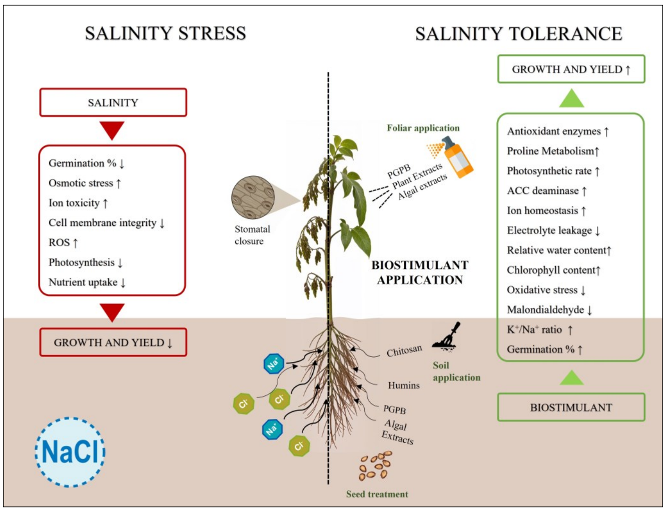

Fig. 3. Impact of salinity stress and biostimulants' effect on plants against salinity stress (ROS-Reactive Oxygen Species, ↑-Increase, ↓-Decrease).

higher than the optimum range. Numerous physiological and biochemical disorders, such as protein denaturation, modifications in membrane fluidity, inhibition of photosynthesis and oxidative damage, might result from this stress. Ultimately, these consequences lower agricultural yields and plant productivity. Effective heat stress management is critical for maintaining agricultural productivity in the face of global climate change. Due to heat-induced cell damage, disruptions to protein synthesis and the inactivation of certain enzymes, global warming may have a drastic effect on crop production (4).

Cold stress in plants is the negative impact that low temperatures can have on plant growth, development and survival. It includes freezing injury, which happens when temperatures drop below freezing and ice forms within plant tissues, as well as chilling injury, which occurs at temperatures above freezing but still low enough to cause damage. These circumstances can disrupt photosynthesis, interfere with metabolic processes and harm cells, all of which could have an impact on the general well-being and yield of the plant. Plants respond to cold stress in a variety of ways, including modifying membrane composition, producing antifreeze proteins and collecting suitable solutes like sugars and amino acids to preserve their cells. Cold stress limits plants from expressing their full genetic potential by directly inhibiting metabolic responses and indirectly through cold-induced osmotic (chilling-induced restriction of water uptake and freezing-induced cellular dehydration), oxidative and other stressors (79).

Role of biostimulants under temperature stress : Biostimulants help plants cope with temperature stress by enhancing root development, increasing chlorophyll synthesis and improving photosynthetic rates. They promote plant vigor and overall development in both low and high-temperature stress conditions. Different biostimulants have different impacts on plant tissues, with some encouraging aboveground growth more successfully and others concentrating on root system development (Fig. 4).

Seed treatment : Seed treatment with KIEM® biostimulant (lignin derivative, containing plant-derived amino acids and molybdenum) promotes germination, restores oxidative balance, activates antioxidant defenses and controls gene expression for antioxidant enzymes in cucumber. The biostimulant's effects serve to mitigate the harmful impact of heat stress on germination and growth, making it an effective tool for enhancing plant resistance in severe environmental conditions (80) (Table 2).

Soil application : Irrigation with extracts from brown seaweed *Ascophyllum nodosum* protects membrane integrity reduces tissue damage and influences the expression of genes associated with the stress response, which causes *Arabidopsis thaliana* to exhibit freezing stress resistance under *in vitro* and *in vivo* (81) (Table 3). Silicon treatment (fertigation) stimulates the synthesis of phytohormones such as salicylic acid (SA), abscisic acid (ABA) and jasmonic acid (JA) in maize seedlings in response to chilling stress (82) (Table 3).

Foliar application : Potato heat tolerance is improved with foliar application of Quantis™ biostimulant (a natural by-product of the fermentation of sugarcane and yeast, contains amino acid, organic carbon enriched with potassium and calcium), which decreases the thermal dissipation of excitation energy and increases PSII photochemical efficiency. It activates genes that have antioxidant properties, like β-glucosidases, flavonoid 3′-hydroxylase and PR10. Quantis™ also modifies the activity of cytokinin (CK) and abscisic acid (ABA) in leaves, which promotes larger tuber size, higher weight and enhanced root growth, hence lowering the negative effects of heat stress on potato growth (83) (Table 4). Foliar application of F4.3S minimizes cold stress in zucchini plants by increasing photosynthetic efficiency, minimizing excessive stomatal closure, sustaining a high rate of net photosynthesis and limiting reactive oxygen species (ROS) production. Furthermore, it promotes the build-up of anti-stress molecules that are protective, such as proline and carotenoids, which help the plants recover more quickly after stress. When F4.3S is applied to zucchini plants under cold stress, it has a detoxifying or recovery effect that improves growth and increases stress tolerance (66) (Table 4). Humic acids improve low-temperature stress tolerance in zucchini seedlings by lowering oxidative damage through improved antioxidative enzyme activity and soluble sugar and proline concentrations. Additionally, the expression of genes involved in signaling pathways, phytohormone metabolism and ROS scavenging is modulated by humic acids. This modulation improves low-temperature stress tolerance in zucchini seedlings by reprogramming plant metabolism and increasing the plant's ability to cope with stress conditions (84) (Table 4).

Biostimulants in overcoming heavy metal stress

Heavy metal stress : In plants, heavy metal stress is the detrimental effect of having too much lead (Pb), cadmium (Cd), mercury (Hg) and arsenic (As) accumulated in plant tissues. These metals can cause toxicity symptoms such as stunted growth, reduced photosynthesis, nutritional imbalances and oxidative stress by interfering with several physiological and biochemical processes. Both natural and man-made processes, including mining, industrial pollution and the use of tainted water and fertilizers, can result in heavy metal stress. Important outcomes of heavy metal

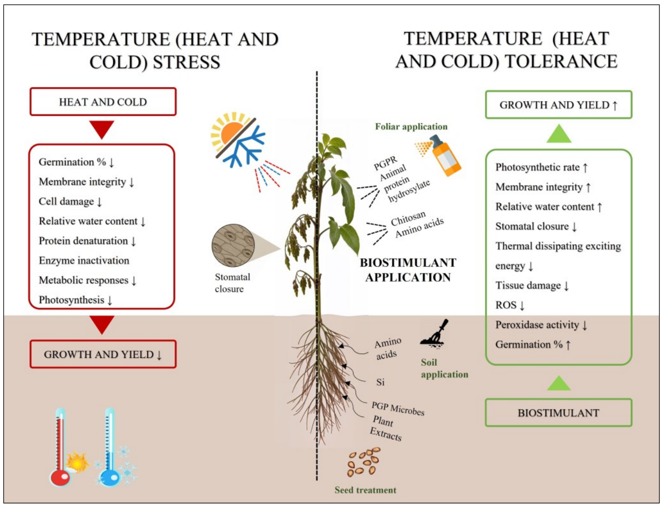

Fig. 4. Impact of temperature stress and biostimulants' effect on plants against temperature stress (ROS-Reactive Oxygen Species, ↑-Increase, ↓-Decrease).

exposure include (a) Oxidative stress: Increased production of reactive oxygen species (ROS), which causes cellular damage (b) Enzyme inhibition: Important proteins and enzymes can bind to heavy metals and become inactive (c) Nutrient imbalance: A disruption in the absorption and movement of essential nutrients (d) Growth inhibition: Stunted development as a whole, reduced growth of roots and shoots and chlorosis of leaves (85). High levels of heavy metals can have direct harmful effects on cells, such as inhibiting cytoplasmic enzymes and causing oxidative stress that damages cellular structures. The reduction in the amount of beneficial soil microorganisms caused by the elevated levels of metal may result in a decrease in the breakdown of organic matter, causing a reduction of particular nutrients in the soil (86).

Role of biostimulants under heavy metal stress : Certain amino acids, such as proline, have been shown to exhibit chelating properties. These activities can protect plants against heavy metals as well as facilitate the uptake and transport of micronutrients. Some nitrogenous molecules, such as proline and glycine betaine scavenge free radicals and so provide antioxidant activity that helps to mitigate environmental stress (8). Biostimulants containing peptides and amino acids as active components can improve plant tolerance to heavy metals. Among the amino acids, increasing the amount of proline in plants is very useful in their defense since it can chelate metal ions within plant cells, act as an antioxidant and play an important role in osmoregulatory activities. Humic substances can interact with heavy metals and complex them with carboxylic and phenolic hydroxyl groups, reducing heavy metal mobility in soil and, as a result, their bioavailability to plant roots (Fig. 5).

Soil application : Soil application with *Bacillus* spp. helps in alleviating heavy metal stress in crops by reducing heavy metal toxicity through mechanisms such as biosorption, chelation and production of antioxidant enzymes. They also improve nutrient availability by fixing nitrogen, solubilizing phosphorus, zinc and potassium and producing siderophores, which enhance nutrient uptake by plants (64). The potential of heavy metal-stressed spinach plant bioremediators, such as microorganisms resistant to heavy metals that were isolated from industrial effluents. Three isolates were chosen because they are highly resistant to heavy metals. The isolates were identified as *B. subtilis* subsp. *spizizenii* DSM, *Paenibacillus jamilae* DSM and *Pseudomonas aeruginosa* DSM. Heavy metal-resistant bacteria increased the fresh and dry weights, chlorophyll content, transpiration rate, net photosynthesis, stomatal conductance, relative water content and membrane stability index of spinach plants, compared to control plants (87) (Table 3). Seaweed extracts from *Cystoseira ericoides*, *Ulva lactuca* and *Fucus spiralis* were investigated in tomatoes using biostimulants that promote Pb tolerance by lowering anthocyanin and proline content (88) (Table 3). Inoculation with *Glomus* spp., either alone or combined with *Rhizobium leguminosarum*, effectively enhanced the establishment of mycorrhizal colonies and can dramatically enhance date palm root vigor and biomass accumulation under Pb stress. As a result, inoculating date palms with *Glomus* spp. and *Rhizobium leguminosarum* can increase Pb tolerance in date palms (89) (Table 3).

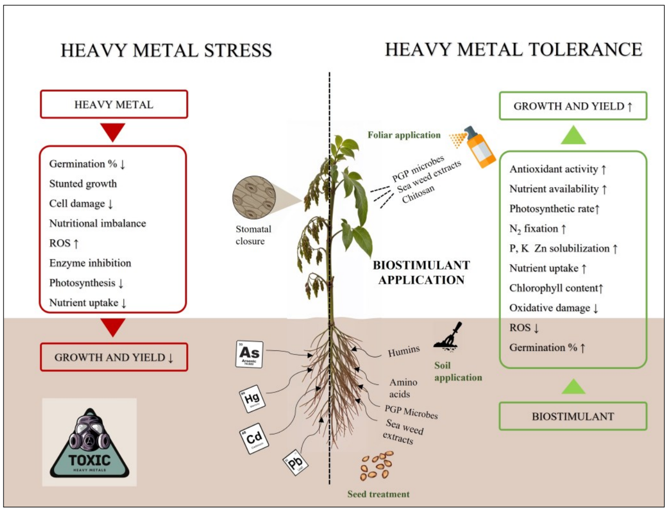

Fig. 5. Impact of heavy metal stress and biostimulants effect on plants against heavy metal stress (ROS-Reactive Oxygen Species, ↑-Increase, ↓-Decrease, N-Nitrogen, K-Potassium, Zn-Zinc).

Biostimulants in Overcoming Nutrient Stress

Nutrient stress : Nutrient stress in plants refers to the adverse effects caused by an imbalance in the availability of essential nutrients required for their growth and development, which can result from either a deficiency or an excess of these nutrients. Plants need a range of nutrients, including macronutrients like nitrogen, phosphorus and potassium, as well as micronutrients like iron, manganese and zinc, to support various physiological processes. Their deficiency can lead to symptoms like chlorosis, necrosis and stunted growth, impacting crop yield and human nutrition. Plants may experience nutrient stress due to several reasons. One main factor is the variation in soil composition, which can leave certain areas deficient in vital nutrients and induce stress in plants. Furthermore, overuse of chemical fertilizers can deplete or disrupt soil nutrients, worsening the problem. Nutrient stress can also be caused by environmental variables that limit the uptake of nutrients by plants, such as heat stress, pH fluctuations and soil pollutants. Furthermore, crop productivity and plant growth can be greatly impacted by an unbalanced nutritional regime in the soil. Co-limitation, in which a nutrient is required to access another, can exacerbate nutrient stress situations, affecting overall plant health and productivity (90, 91). Overreliance on chemical fertilizers to address nutrient stress can lead to environmental concerns like eutrophication and soil fertility loss. Exploring natural adaptive mechanisms in plants can help develop nutrient deficiency-tolerant crop varieties and reduce dependence on harmful fertilizers.

***Role of biostimulants under nutrient stress* :** Biostimulants play a significant role in enhancing plant growth and development under nutrient-stress conditions by promoting root growth, increasing nutrient uptake efficiency and improving nutrient availability. They can help plants overcome biotic or abiotic stresses, leading to better adaptation and resilience. By stimulating root branching, hormonal action and promoting synergy between mycorrhizal fungi and plants, biostimulants contribute to maintaining plant health and productivity even in challenging nutrient-deficient environments (92) (Fig. 6).

***Seed treatment* :** Microalgal extracts play a role in enhancing the uptake of essential nutrients by plants through seed treatment and foliar spraying. This method allows for faster absorption of water-soluble metabolites by the leaves, promoting nutrient translocation throughout the plant. The extracts can influence plant growth rate, shoot length and leaf number, ultimately improving the physiological processes related to nutrient uptake and utilization in tomatoes. Seed treatment with microalgal extracts has a positive effect on the nutrient uptake of tomatoes (69) (Table 2). Immersion of planting material (cuttings) in chitosan solution at 1000 ppm significantly enhanced *Salicornia bigelovii* growth and flowering compared to the control, by up to 64% and 47% respectively. Through a variety of methods of action, chitosan probably improved the plant's ability to absorb water and nutrients, increased the amount of nitrogen available and promoted growth and flowering (93) (Table 2). The addition of humic and fulvic acids increased the availability of zinc and phosphorous in the soil, which improved their absorption by the plant. As a result, maize plant growth and production traits improved (94) (Table 2).

***Soil application* :** Onion Juice Concentrate (OJC) improved the growth of bok choy, lettuce and radish using a variety of application strategies. Bok choy, lettuce and radish all had better root growth after subirrigation with OJC. Integrating foliar and subirrigation treatments enhanced the root development and nutrient uptake in radish and bok choy (37, 95) (Table 3).

***Foliar application* :** The foliar application of microalgal extracts plays a crucial role in enhancing the uptake of essential nutrients in tomatoes (69) (Table 4). The application of humic acid and seaweed extract (*Kappaphycus alvarezii*) foliarly significantly increased root and shoot length in tomato plants, enhancing overall growth and productivity (9) (Table 4). When OJC was applied foliarly at doses of 1% to 2%, bok choy production and overall growth increased. Improved root development will result in more effective use of nutrients and water, which will gradually improve the resilience and general health of the plant, especially in the aboveground sections (95) (Table 4).

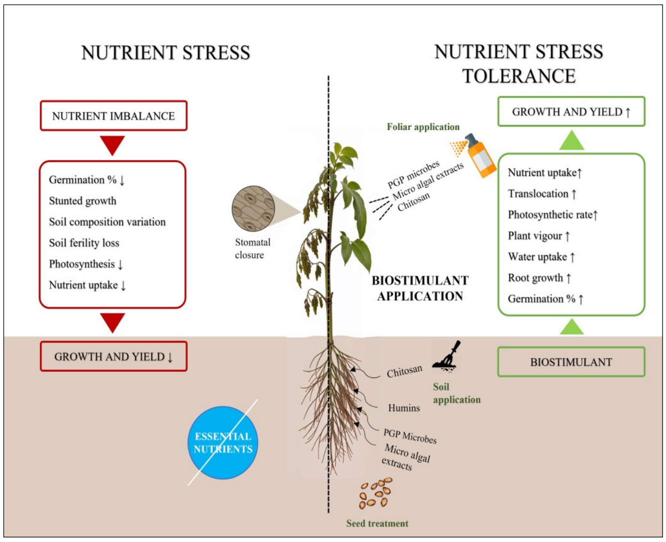

Fig. 6. Impact of nutrient stress and biostimulants's effect on plants against nutrient stress (ROS-Reactive Oxygen Species, ↑-Increase, ↓-Decrease).

Table 2. Effect of seed treatment of biostimulants in different crops

Sl. No.	Crop	Biostimulant	Effect	Reference
1	*S. bigelovii*	Chitosan	Enhanced yields	(93)
2	Wheat	Maize grain extract (MGE)	Salinity tolerance	(63)
3	Wheat	*B. subtilis*	Salinity tolerance	(72)
4	Soybean	Chitosan	Salinity tolerance	(73)
5	Maize	Humic and fulvic acids	Improves plant growth and production traits	(94)
6	Cucumber	KIEM®	Heat tolerance	(80)
7	Tomato	Microalgal cellular extracts	Increased germination and plant growth rate	(69)

Table 3. Effect of soil application of biostimulants in different crops

Sl. No.	Crop	Biostimulant	Effect	Reference
1	Spinach	*B. subtilis* subsp. *spizizenii* DSM, *P. jamilae* DSM and *P. aeruginosa* DSM	Heavy metal tolerance	(87)
2	Tomato	Seaweed extracts	Pb tolerance	(88)
3	Maize	Brown macro-seaweeds - *I. stellata* and *C. sinuosa*	Salinity tolerance	(74)
4	Date palm	*Glomus* spp. and *R. leguminosarum*	Pb stress	(89)
5	Mexican lime trees	Humic acid	Salinity tolerance	(75)
6	Maize	Silicon	Chilling tolerance	(82)
7	Bok Choy Radish	Onion Juice Concentrate (OJC)	Enhance the growth and yield	(95)
8	Lettuce	Onion Juice Concentrate (OJC)	Enhance the growth and yield	(95)
9	Wheat, Maize, Chickpea, Rice	*Bacillus* spp.	Salinity tolerance	(64)
10	*A. thaliana*	Brown seaweed (*A. nodosum*)	Freezing tolerance	(81)

Table 4. Effect of foliar application of biostimulants in different crops

Sl. No.	Crop	Biostimulant	Effect	Reference
1	Potato	Quantis™	Thermotolerance	(83)
2	Zucchini-Summer squash	F4.3S	Cold tolerance	(66)
3	Zucchini-Summer squash	Humic acids	Low-temperature tolerance	(84)
4	Tomato	Humic acid and seaweed extract (*K. alvarezii)*	Better growth, yield and quality	(9)
5	Savory (*S. hortensis* L.)	Chitosan	Salinity tolerance	(77)
6	Pepper *(C. annuum* L.)	Animal protein hydrolysate	Salinity Tolerance	(76)
7	Bok choy Radish	Onion Juice Concentrate (OJC)	Enhance the growth and yield	(95)
8	Tomato	Microalgal cellular extracts	Increased germination and plant growth rate	(69)

Limitations

Specific types of biostimulants offer unique benefits. Humic substances improve soil structure and nutrient availability, aiding plants under drought and nutrient-deficient conditions. Seaweed extracts enhance water retention and seed germination, while protein hydrolysates boost nitrogen metabolism and stress recovery. Chitosan activates defense mechanisms against extreme temperatures and salinity and mycorrhizal fungi enhance phosphorus uptake and plant health. Beneficial bacteria improve nutrient uptake and drought resilience, enabling targeted agricultural applications (96).

The effectiveness of biostimulants is significantly influenced by environmental factors such as soil type, temperature and moisture levels. Soil type affects microbial activity and nutrient cycling, with higher efficacy in organic-rich soils. Temperature impacts microbial functionality, enhancing biostimulant effectiveness at optimal levels while mitigating stress under high temperatures. Moisture levels are crucial, as biostimulants improve water retention and activate soil enzymes for nutrient cycling. Tailoring biostimulant applications based on these factors can enhance crop resilience and productivity in various agricultural contexts. Microbial biostimulants are generally more effective in enhancing nutrient uptake and soil health, while non-microbial types are beneficial for improving soil structure and water retention. Their efficacy tends to increase in soils with low organic matter and nutrient deficiencies (97, 98). Understanding these differences is necessary for the optimized use of biostimulants to address specific agricultural challenges effectively.

Biostimulants only emphasize their significance in enhancing the efficiency of plant growth and yield under stress conditions and do not affect plants under ideal conditions. Even though they show a positive impact they do not necessarily show considerable impact on the crop yield. Also, biostimulant application methods might vary in terms of efficiency, quantity required and environmental effect, focusing on the importance of thoughtful consideration and suitable application procedures. The composition of biostimulants remains a major source of concern. The efficiency of biostimulants is determined by their composition, which might be difficult to describe due to the inclusion of several bioactive compounds. Potential drawbacks include short-lived effects on soil microbial communities and the risk of disrupting existing microbial dynamics if applied improperly. So, Continuous use of biostimulants requires careful monitoring to ensure they do not adversely affect indigenous microbial diversity or soil health over time (99). Barriers to the adoption of biostimulants in agriculture include regulatory hurdles due to inconsistent global definitions, market acceptance influenced by consumer skepticism, variability in product quality and higher production costs (100). Addressing these issues is essential for promoting effective use.

Conclusion and Future Perspectives

Biostimulants play a significant part in protecting plants from the damage caused by abiotic stress. Drought, salinity, severe temperatures, heavy metals and nutritional imbalances may reduce agricultural yields and cause financial losses by stressing plants. Furthermore, it has been demonstrated that the use of these biostimulants increases overall plant growth and productivity as well as photosynthetic efficiency and water use efficiency under stressful situations. Integrating biostimulants into existing agricultural practices can enhance their effectiveness. This includes incorporating them into soil management strategies or applying them alongside traditional fertilizers to improve nutrient uptake efficiency. Strategies include precision agriculture, tailored applications and farmer education to optimize benefits while minimizing ecological impacts. Monitoring soil health is crucial for maintaining biodiversity and maximizing long-term advantages. Utilizing high-throughput phenotyping and metabolomics can help identify optimal application methods and timings. Currently, biostimulants have shown promising economic rise in the field of agriculture but their effect can be elevated with the help of the development of new biostimulants which will show positive attributes in different crops. The implication of biostimulants results in increased yields and product quality, reduced input costs through enhanced efficiency, improved resilience against climate change impacts and participation in a growing market focused on sustainability. Overall, biostimulants represent a promising avenue for improving ecosystem sustainability by enhancing plant resilience against climate change impacts while contributing to yield improvements. However, addressing the challenges related to their application will be essential for maximizing these economic benefits in the agricultural sector. Much more research should be conducted to study their tendency to alter the effect implicated by the stressors. The mechanism of biostimulants based on the climatic condition alters their impact on the physiology of the plants which will be a better understanding towards the formulation of the biostimulants. A thorough proteomic and transcriptomic study of the biostimulant will help us understand the mechanism behind the mitigation of plant growth reduction under stress. Since biostimulants improve physiological functions, change gene expression and increase antioxidant activities to improve plant stress tolerance and their efficacy is maximized under stress conditions, exploiting biostimulants is crucial to ensure environmental, food and sustainable agricultural concerns. We should also focus on improving their effects on the plants even during the optimal condition as biostimulants only act under stress, which will be a breakthrough discovery in the field of biostimulants. Formulation of nano biostimulants and combining different biostimulants like microbial and non-microbial biostimulants in such a way that they yield an advantageous influence over crop growth and productivity will pave the way for the potential long-term solutions for improving agricultural yield and resilience in the face of mounting environmental challenges brought on by climate change.

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Authors' contributions

All authors have contributed to the writing, editing, summarizing and revising of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used the Grammarly AI tool to check the grammar in the manuscript. After using this tool, the authors reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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