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REVIEW ARTICLE

Biostimulants: Mitigation strategy for salinity stress in fruit crops

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Abstract

The burgeoning specter of abiotic stresses caused by global climate change, including drought, salt, extremely high temperatures, heavy metals and UV radiation, has rendered fragile agroecosystems increasingly precarious. This has reduced the production and quality of fruit crops. The burden on plants might be even worse if several stressors occur at once. These multifarious stressors have led to a 70 % reduction in annual agricultural production globally, sparking the embers of food scarcity and stoking the fires of hunger within our ever-expanding populace. However, within this seemingly hopeless situation, a number of alternatives have surfaced as a glimmer of light. Biostimulants, derived from natural or organic sources, enhance plant development and resilience by enhancing their capacity to absorb nutrients, withstand stress and sustain overall health. The exogenous application of biostimulants on an organic basis has emerged as a powerful treatment for certain of them, promoting plant growth and production in the face of adversity. These biostimulants work across a wide range of pathways, composing a symphony of resistance to stress-related difficulties. Only a few papers have provided information on plant biostimulants' impacts on fruit quality, which is connected to appearance, chemical composition and physical characteristics. The objective of this review is to assess the efficacy of externally applied organic biostimulants in improving plant growth and productivity, especially in challenging environments. These biostimulants enhance plant resilience, nutrient absorption and overall health, providing a sustainable solution to agricultural difficulties. They also have a sustainable appeal since they are organic, satisfying the desire of customers who are concerned about the advantages of eating healthier food.

Keywords

abiotic stress; biostimulants; climate change; salinity stress; sustainable fruit production

Introduction

The rapid onset of climate change has intensified biotic and abiotic stresses, causing significant changes in the physiological, biochemical, cellular and molecular processes of plants (1). The growing impacts of global warming pose a significant danger to sustainable food production worldwide, as they affect plant development, crop yields and nutritional quality (2). Humanity significantly relied on large-scale chemical inputs to boost crop productivity throughout the decades of the industrial revolution, permanently disturbing the ecological balance (3). Intensive human activities, rapid industrialization and the current effects of climate change have led to a decrease in the quality of arable land and environmental degradation, including an excessive accumulation of heavy metals in the soil (4). All living organisms encounter many forms of environmental stress at different stages of their lives. Individuals with genetic resilience have enhanced abilities to endure or evade the detrimental impacts of stress on their physiological systems, thereby enabling them to thrive, progress and survive more efficiently. Plants often experience a variety of environmental stressors under natural climatic and field conditions, including drought, salt, severe temperatures, heavy metals and UV radiation, which increases the intensity of the combined stress (5). Not all organisms have the capacity to evolve their plastic responses and flourish in such severe conditions to adapt to these pressures (6). The U.S. National Climate Assessment estimates that environmental pressures are responsible for crop output losses of up to 50 %. In this regard, we see synthetic fertilizers (like nanosilicon and FeO nanoparticles) and pesticides as important horticultural inputs and we have developed several methods to mitigate the negative environmental consequences (7). The unbalanced use of these pesticides, while increasing crop output, also harms the environment and has an effect on human health. Alternatives to traditional or conventional agrichemicals are in greater demand. The study examines how plants respond to stress at many levels, from their phenology to their molecular biology and it has many different features that vary in approach, research technique, inquiry degree and plant species consideration (8). It is well known that human activities and extreme weather changes cause a lot of environmental and abiotic stresses. These stresses create a lot of reactive oxygen species (ROS), which are made up of free radicals and non-radical molecules. These molecules then cause oxidative stress in plants (9). There is an increasing demand for alternatives to traditional or conventional agrichemicals. There are many aspects of this research, differing in the approach, research methodology, investigation level and consideration of plant species, whereas scientists explore plant responses to stress within the range from their phenology to molecular biology. Anthropogenic activities and harsh climate changes are known to cause a variety of environmental and abiotic stresses that affect plants. These stresses include too many reactive oxygen species (ROS), which include free radicals and non-radical molecules (10). Horticulturalists urgently require crop production methods that are effective in a range of challenging environmental situations, including drought, flooding, salinity and nutrient imbalances in soil or nutrient solutions, heavy metal toxicity, extremely high temperatures and other stressful situations (11).

Fruits are a vital component of the human diet due to their nutritional advantages. These crops not only contribute significantly to dietary security but also provide the farming community with productive work and increased revenue (12). However, the abiotic stressors they experience throughout key growth phases have a negative impact on their production. Climate change also predicts that abiotic stressors will occur more frequently and last longer. In India, salt, high temperatures and drought are the primary abiotic factors that harm tropical fruit crops. The morphological, anatomical, physiological and biochemical changes brought on by these pressures have an impact on both the organisms' production and quality (13). Therefore, a full understanding of the negative effects of abiotic stressors on various crop species is essential for developing creative horticulture practices to counteract the negative effects. Physical (weight, firmness and colour), chemical (soluble solids content, titratable acidity and pH) and nutritional (phenolic content and antioxidant capacity) characteristics all influence the quality of edible fruits, ultimately determining consumer security and preferences (14). The fruit's appearance, which includes visual characteristics such as shape, size, colour consistency, damage marks, maturity level and weight, largely determines consumer choice (15). The primary goal of post-harvest technology has been the preservation of aesthetic quality, even if this is not a guarantee of internal quality. The desire for "functional foods" and consumers' increased interest in the nutritional advantages of fruit intake, however, are shifting this perception (16). Biostimulants not only enhance resistance to stress but also promote seed germination, early seedling development and overall plant growth and yield. Biostimulants are used in a sustainable way to make plants more resistant to biotic and abiotic stresses. However, studies have shown that they can also help seeds germinate, speed up the early stages of seedling development, improve soil nutrient uptake and increase plant growth (biomass accumulation) and yield (17).

Depending on the doses utilized, biostimulants are cutting-edge technologies that fall between fertilizers and plant growth regulators. These can be organic or inorganic products that have microorganisms or bioactive compounds that, when added to the plant or rhizosphere, help the plant grow and produce more by improving its ability to take in nutrients and use them effectively, its ability to handle stress or the quality of the product (18). Additionally, it may be made from food waste and agricultural by-products. By-products serve as the primary raw material for the creation of biostimulants as part of the circular economy plan to create an increasingly sustainable agriculture (19). Researchers are currently struggling to identify the specific pathways that biostimulants trigger in response to stressful situations. It is plausible that the bioactive chemicals found in these substances could alter plant metabolism by acting on certain pathways, given the physiological effects generated by biostimulants (20). Stressful circumstances may enhance the metabolic pathways activated by biostimulants, aiding plants in adapting, overcoming, or delaying the most difficult situations (21). It's worth noting that metabolites with antioxidant properties frequently increase in plants exposed to biostimulants (22). These defensive molecules significantly diminish the degenerative effects of free radicals that build up in plant tissues under stressed circumstances (23). In the final part of the introduction, the authors should succinctly state the hypothesis that biostimulants enhance fruit crop resilience to abiotic stress by improving stress tolerance and overall plant performance, as well as outline the study's aim, which is to evaluate and synthesize evidence from various research and review articles on this topic.

Mechanism of action of plant-based biostimulants under abiotic stress

The term "Plant Biostimulant" is also applied to commercial products that contain a combination of chemicals or microbes that are intended to enhance plant nutrition and reduce the effects of abiotic stress (24). Between 2017 and 2025, the global biostimulant market is anticipated to expand quickly at a 10.2 % annual growth rate. In contrast, less than 25 % of the commercially available Biostimulant solutions on the global market are microbial-based plant biostimulants (25). They may comprise bacterial endosymbionts, mycorrhizal and non-mycorrhizal fungi and plant growth-promoting rhizobacteria (PGPR), all of which use direct and indirect processes to promote plant growth and development under both typical and stressful circumstances (26). It influences how plants react to diverse stimuli and develop and sustain adequate activity nearby and directly or indirectly assists the growth and development of plants (27). These activities may be active concurrently or sequentially depending on the stage of plant growth and the surrounding environment. Some prominent examples of direct mechanisms include:

i) indole acetic acid (IAA), abscisic acid (ABA), gibberellic acids (GAs) and cytokinins are among the phytohormones that are produced.

ii) biological nitrogen fixation and

iii) enhanced mineral nutrient solubilization is also among them.

Indirect mechanisms include:

i) production of 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase,

ii) production of siderophore,

iii) antioxidant enzyme production,

iv) production of antibacterial and antifungal compounds and

v) production of exopolysaccharides (EPS) and biofilm formation. An important biotechnological strategy for reducing the negative impacts of abiotic stressors on crops in various environmental contexts may be the discovery and deployment of plant biostimulants.

By secreting exogenous hormones and bioactive secondary metabolites that significantly reduce abiotic stress, biostimulants primarily modify the state of plant hormones. The main plant hormone generated by biostimulants is called auxin and distinct bacteria use a number of different routes for this process. A well-researched bacterial and fungal signaling molecule involved in plant-microbe interactions is IAA, which is generated by biostimulants (28). The development and resistance of plants to abiotic stimuli such as heat, salt, heavy metals and drought are improved by a number of GA-producing Biostimulants (9). As they treat abiotic stress while also boosting the available iron transport, modifying Na^+/H^+ antiporters and altering various ion channels, biostimulants that create siderophores may be a potential substitute for chemical fertilizers (29). Similar to this, numerous biostimulants create exopolysaccharides, which are in charge of adhering to soil particles, root surfaces and other microorganisms. Exopolysaccharides are crucial for plant growth because they stabilize soil structure and increase water potential and cation exchange capacity (30). Exopolysaccharides often form an enclosed matrix of microcolonies that offers defense against environmental flotation, water, nutrient retention and epiphytic colonization. By increasing the amount of rhizospheric soil macropores, raising water potential and facilitating plant nutrient absorption, biostimulants enhance soil structure (31). Additionally, exopolysaccharides-producing halotolerant biostimulants can store Na^+ ions taken up by plants, reducing the effects of salt stress (32).

Impact of plant-based biostimulants on fruit crops under abiotic stress

Many experts believe that the most significant environmental factors impacting plant growth, development, productivity and quality are drought, salt, mineral disturbances and temperature stress. The physiological processes occurring at the molecular and cellular levels are the links between these stresses, whereas metabolites are essential for plant survival and adaptability (33). Indeed, various stress types or their combinations may cause the production and activation of several molecules involved in the metabolism of carbon, nitrogen, sulphur and minerals in plants. In addition, a wide range of functional chemicals found in the numerous biostimulants utilized in plant production today can affect the metabolic pathways of treated plants as well as the chemical makeup of plant tissues and organs. There is a need to clarify the interactions between stress and biostimulants in terms of metabolic changes in plants, particularly from the perspective of producing functional foods, in addition to the study on plant response to stress and the support of plant stress tolerance provided by biostimulants (34).

Salinity stress

More than 6 % of the world's land is affected by soil salinization, which reduces agricultural output on 22 % - 33 % of all cultivated and irrigated agrarian land (35). Soil salinity will pose a danger to almost 50 % of arable land by 2050 (36). Salinity stress tolerance has been found to be induced in a variety of crops by a number of plant-based biostimulants. Through a variety of synergistic processes, including osmotic control, higher nutrient absorption, phytohormone signaling and improved photosynthesis, plant growth-promoting biostimulants reduce salt stress (37), as shown in Fig. 1. Furthermore, during salt stress, biostimulants activate various antioxidants, reduce Na absorption, increase N, P and K uptake, raise chlorophyll content and modulate hormonal regulation (38). Salt stress causes plants to develop less slowly and causes cellular damage, which compromises the health and production of the plant (23). The impact on the crop depends on the level of stress and the length of exposure. Due to osmotic stress brought on by the high ionic concentration in the soil and the high salt concentration, roots may be less able to absorb water. Water stress signs are really present in stressed plants (21).

Biostimulants mitigate the salinity stress in fruit crops

As shown in Tables 1 and 2, by enhancing the crop's resistance to salt, biostimulants can reduce its impacts. The inborn defenses against salt are comparable to those shown in plants exposed to drought. Proline, simple sugars, alcohols, abscisic acid and antioxidant substances that might prevent damage brought on by the buildup of free radicals may all see

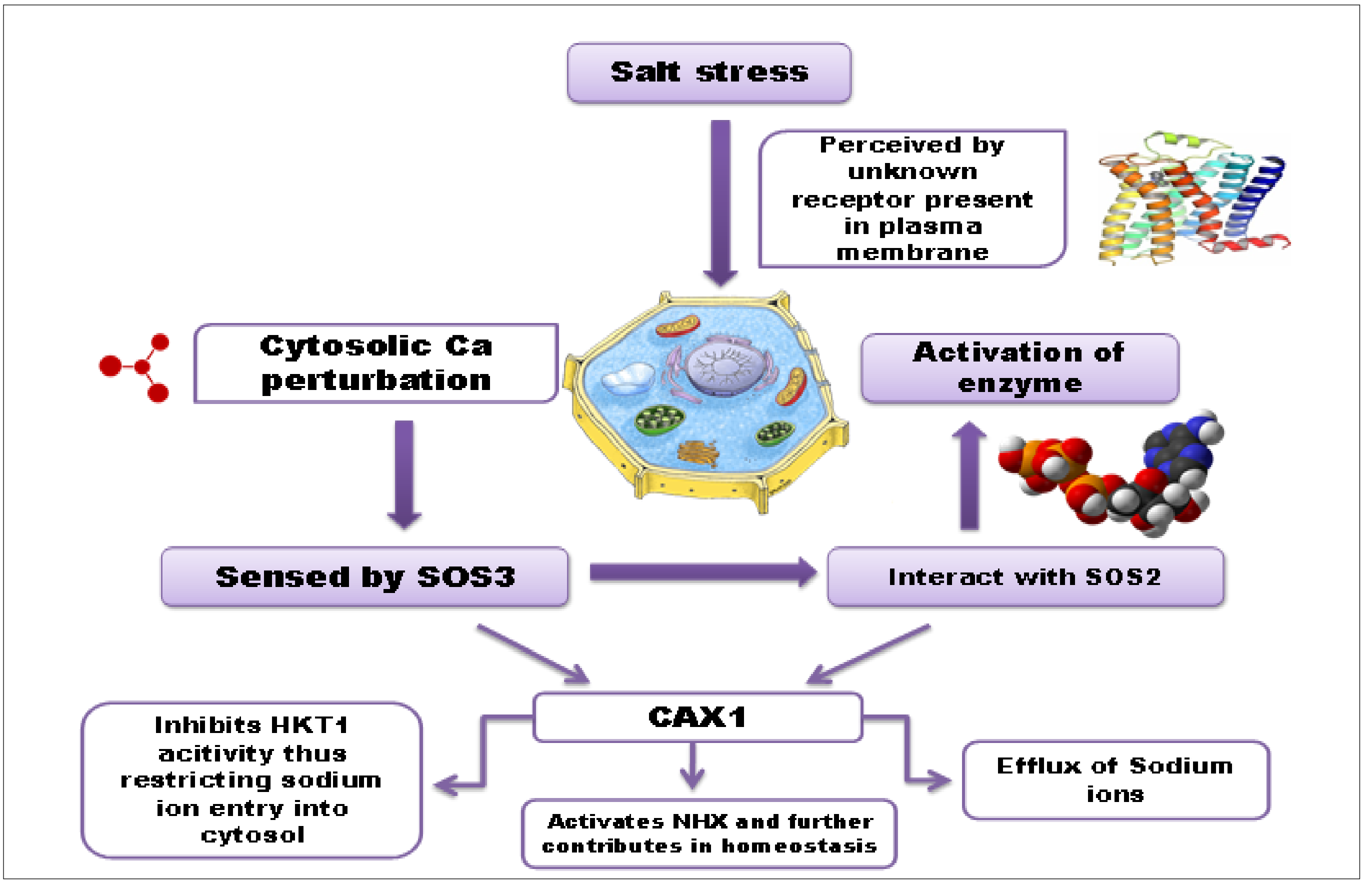

Fig. 1. The figure depicts a cell's response to salt stress, starting with perception by an unknown receptor in the plasma membrane. This triggers cytosolic calcium perturbation, activating an enzyme that interacts with SOS3. SOS3 inhibits HKT1 to restrict sodium entry, activates CAX1 for ion homeostasis and enhances NHX1 function, leading to the efflux of sodium ions, maintaining cellular balance.

Table 1. Effect of biostimulants on fruit crops under salinity stress

Crops	Biostimulants	Effects	Reference
Strawberry	Acadian (*Ascophyllum nodosum*)	↑yield ↑growth ↑root length ↑surface area, volume and number of tips ↑numbers of crowns	(59)
Citrus	Seaweed extract Brown *Ascophyllum nodosum* seaweed extract	↑↑ growth and stem water potential	(60)
Loquat	AMF (*Funneliformis mosseae*)	↑↑ dry biomass and leaf water potential ↑↑ osmotic adjustments at root level (high proline concentration) and to the anti-oxidative molecule (i.e., glutathione)	(61)
Mango	Potassium silicate	↑↑ vegetative and productive growth ↑↑ tolerance to water stressed conditions ↓↓ harmful effects of ROS	(62)
Tangerine orange	AMF (Glomusmosseae and *Paraglomus occultum*)	↑↑ plant growth (height, stem diameter, shoot, root and total plant biomass) ↑↑ photosynthetic rate, transpiration rate and stomatal conductance	(63)
Strawberry	PGPB (*Bacillus subtilis* EY2, *Bacillus atrophaeus* EY6, *Bacillus spharicus* GC	↓↓ Sodium and chloride leaf and root content ↑↑ Increased leaf relative water content and final yield	(64)
Strawberry	AMF (*Funneliformis caledonius*, *Funneliformis mosseae* and *Rhizophagus irregularis*	↑↑ salt tolerance ↑↑ increased shoot and root mass Promotes Genotype specific effect of AMF inoculation	(65)

Table 2. Biostimulants and their effects on different crops under stress conditions, specifically focusing on mitigating salinity stress and enhancing crop productivity and quality.

Biostimulants/Method	Crops studied	Observed effects	Reference
Silicon application	Strawberries	Enhanced phenols and flavonoids concentration, improved photosynthetic rate, although ascorbate content reduced.	(40)
NOM-based biostimulant in GS fertilizer program	Strawberries	Salt stress mitigation; salt-stressed plants with biostimulant had yields 96 % higher than those without.	(41)
Humic acid (HA) and ascorbic acid application	Strawberries (cv. Camarosa)	Improved productivity, titratable acidity, color, total soluble solids, vitamin C content and leaf mineral content (K, P, Ca, Mg).	(42)
Ascophyllum nodosum extract (AE)	Grapes	Increased phenolic compounds and antioxidant capacity; elevated anthocyanin levels, enhanced enzyme activity and gene expression linked to anthocyanin production.	(45, 46)
Sunred® biostimulant and S-ABA application	Red Globe grapes	Increased anthocyanin levels, attributed to enhanced enzyme activity and gene expression related to anthocyanin production.	(47)
Lupine hydrolysates and milk casein	Corvina grapes	Increased anthocyanin content, improved color and decreased water loss.	(47)
Humic acid application	Italian grape varieties (Riesling, Feteasca Regala)	Increased total soluble solids, influenced by casein, soybean and lupine hydrolysates.	(47)
Biostimulant application (Biozyme crop plus®, Cytokine spic®, Vipul®)	Pomegranates	Reduced fruit cracking, enhanced fruit length, diameter, weight, volume and color.	(48-50)
Ascophyllum nodosum (AE), Vitamin B, Alfalfa-based plant hormones	Red Jonathan apples	Increased phenolic compounds, improved antioxidant capacity, enhanced red hue due to higher anthocyanin concentrations and reduced "Jonathan spot" by over 50 %.	(51 , 52)
Various products and biostimulants (Sunred®)	Apples (cv. Red Jonathan)	Diverse results, influencing fruit ripening and reducing physiological disorders.	(53)
Agro-industrial residue extract	Kiwi (cv. Hayward, Green Light)	Increased fruit weight and ascorbic acid content; noticeable increase in antioxidant capacity in Hayward cultivar.	(53)
Plant biostimulants (Hendophyt® PS, Ergostim® XL, Radicon®)	Kiwi (cv. Orange Rubis)	Rapid fruit ripening, increased first harvest percentage and enhanced oxidative stress resistance.	(54, 55)
Ascophyllum nodosum extract (AE)	Oranges	Increased total soluble solids, decreased titratable acidity and advanced fruit harvest by up to seven days; noted 15 % productivity increase.	(56, 57)
Ascophyllum nodosum extract (AE)	Cherries (cv. Sweetheart, Skeena)	Decreased cracking index, increased fruit breadth, weight, diameter, pH and wax content; no changes in production or nutritional qualities.	(58)
Biostimulant from decomposed chicken feathers	Bananas	Increased protein, amino acids, reducing sugars, phenolics and flavonoids in mature fruits; root treatment more effective than foliar spray in promoting these changes and yield increase.	(59)

concentration increases as a result of biostimulants (39). The use of biostimulants leads to improved resistance to stress and decreased production losses. The species and the salt stress conditions influence the number of applications. Inhibiting sodium entry while promoting potassium and calcium uptake results in decreased Na^+/K^+ and Na^{+}/Ca^{2+} ratios; consider this mechanism to be one of the main ways to improve plant root and shoot growth and productivity under salt stress conditions, as shown in Fig. 2 (49). When strawberries are cultivated under salt stress, the application of silicon can enhance some fruit quality indicators, such as the concentration of phenols and flavonoids. Siliforce®, a Si-containing biostimulant, was applied to strawberries growing under nutrient restriction and the strawberries photosynthetic rate increased considerably 24 h later compared to control plants, although the ascorbate content of the fruit was reduced (40). Once more, an experiment was undertaken (41) to examine the effects of induced salt stress on strawberry plants and the efficiency of a biostimulant based on natural organic matter (NOM) in reducing this stress as part of a grower standard (GS) fertilizer programme. The findings were illuminating and showed how the strawberry crop was severely stressed by salt inclusion in irrigation water, which resulted in a considerable decrease in production. The NOM-based Biostimulant's inclusion in the GS programme, however, turned out to be a game-changer. Without the use of Biostimulants, salt-stressed GS plants produced just 20 % as much fruit during the first harvesting month. The cumulative yields of the stressed plants still fell short of those of the non-stressed plants despite the fact that they started to recover in the second picking month. By the end of the study, the salt-stressed plants treated with biostimulant had yields that were

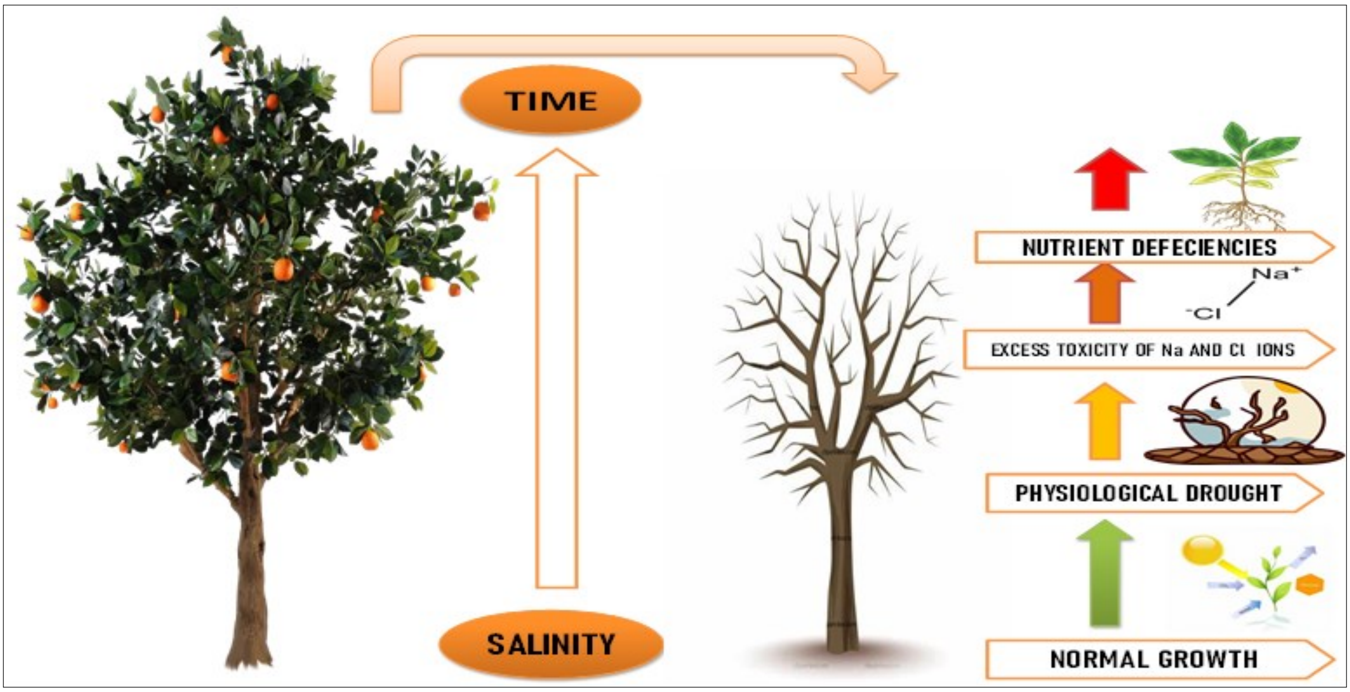

Fig. 2. Effect of salt stress on plant growth and development.

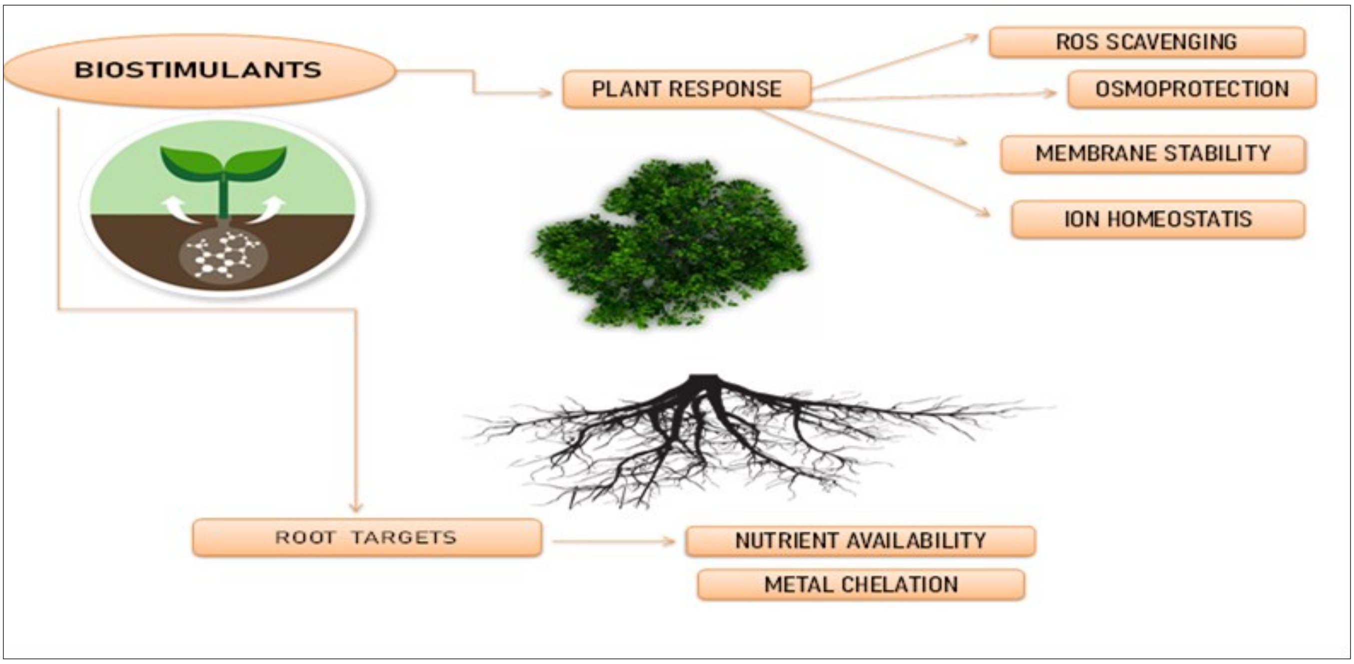

Fig. 3. Response of biostimulants on root and shoot system of fruit tree.

comparable to, if not greater than, those of untreated plants. The most startling finding was how salt stress mixed with the NOM-based biostimulant not only neutralised the negative effects but also produced an astounding 96 % higher yield in stressed plants than those receiving GS alone. Using HA externally improved the cv. Camarosa strawberries' productivity, titratable acidity, colour and total soluble solids and vitamin C contents. K, P, Ca and Mg levels in the leaves also increased. However, the results of untreated plants revealed an increased BRIX-to-acidity ratio and an increased overall antioxidant capability. When sprayed with salicylic acid, the same cultivar exhibited increased yield, vitamin C, total soluble sugars, total acidity, total antioxidant capacity, greater P and Ca leaf contents and enhanced fruit redness. Overall, 25 mg L^{-1} of HA and 2 mM of ascorbic acid were the optimum concentrations that produced exceptional results (42).

This study highlights the biostimulant capacity to reduce salt-induced stress, providing producers with an encouraging tool to protect crop output and resilience in the face of difficult environmental circumstances. Because phenols are powerful antioxidants, they are essential for raising the nutraceutical value of food (43). Phenolic chemicals have a particularly important role in wine quality, impacting the total quality of grapes used in winemaking (44). It has been shown that applying *Ascophyllum nodosum* extract (AE) to grapes can increase the manufacture of these vital substances. Research by Norrie, Branson, and Keathley showed that AE had a favourable effect on grape quality and yield (45). In trials using 2 distinct dosages of AE (1.5 and 3.0 kg/ha), found that the fruits of treated plants had greater phenol levels than those of untreated plants (46). The authors also observed elevated anthocyanin levels, which are crucial for determining the look and quality of fruits. By applying Sunred® biostimulant and S-ABA separately to Red Globe grapes prior to fruit ripening, elevated anthocyanin levels were found in the grapes (47). This was ascribed to increased enzyme activity and gene expression linked to anthocyanin production. In a different investigation, the anthocyanin content of Corvina grapes was increased by lupine hydrolysates and milk casein, increasing colour and decreasing water loss. When humic acid was applied to Italian types of Riesling and FeteascaRegala, the total soluble solids in the grapes rose due to the combined effects of casein, soybean and lupine hydrolysates. Pomegranate fruit's aesthetic attractiveness is essential to their economic success. If they are not contaminated by fungi, cracked fruits, which lose value in the fresh market, are usually limited to fruit juice applications. Three commercial plant biostimulants were tested in a study assessing the effect on the quality of pomegranate fruit: Biozyme crop plus® (Biostadt, Mumbai, India) with hydrolyzed enzymes, proteins and algal extract from A. nodosum; Cytokine spic® (Spic, Chennai, India) with gibberellic acid, auxins, cytokinins, algal extract from *A. nodosum*, pH regulators and certain nutrients; and Vipul® (Godrej Agrovet Ltd., Sachin, India) containing triacontanol found naturally in beeswax and vegetable waxes. The results indicated that all the tested plant biostimulants significantly reduced fruit cracking, with higher effectiveness observed at elevated doses. Additionally, these biostimulants were associated with longer fruits, increased diameter, weight and volume. Furthermore, one of the biostimulants even enhanced the color of the fruits. Due to the diverse composition of these products, pinpointing whether the observed effects were solely due to growth regulators or other components proved challenging. Nevertheless, the authors suggested that the reduction in fruit cracking could be attributed to the action of auxins, gibberellins and the activity of hydrolytic enzymes, which collectively enhance the elasticity of cell walls (48).

Previous studies on gibberellic acid supported these findings, revealing its influence on cell wall elasticity, fruit size and control of pomegranate fruit cracking (49, 50). Red Jonathan apples with *Ascophyllum nodosum* (AE), vitamin B and alfalfa-based plant hormones applied separately showed higher amounts of phenolic compounds and improved antioxidant capacity. The increased concentration and consistency of the red hue were ascribed to higher anthocyanin concentrations in the fruit peel (51). The same study found that a combination of zinc and amino acids (glycine, proline, hydroxyproline, glutamic acid, alanine and arginine) reduced the occurrence of "Jonathan spot," a common physiological condition in Red Jonathan apples, by more than 50 % (52). Conversely, applying other products (minerals, organominerals) and the plant biostimulantSunred® (BiochimS.p.a., Medicina, Italy)-which is made of plant extracts, methionine, phenylalanine and monosaccharides-during the apple fruit ripening stage of the CVS produces diverse results (53). They examined the effects on 2 kiwi cultivars, Hayward and Green Light, using an extract obtained from agro-industrial residues that included a multitude of peptides, amino acids and hormones (such as auxins, gibberellins and cytokinins). The fruits of both varieties were heavier and contained more ascorbic acid. Only the Hayward cultivar showed a more noticeable increase in antioxidant capacity, though. This implies that the particular genotype of the plant influences how effective the plant biostimulant is. The plant biostimulants Hendophyt® PS (Iko-Hydro, Rutigliano, Italy), Ergostim® XL (Sumitono Chemical Italia, Milan, Italy) and Radicon® (Fertek, Calvizzano, Italy) are commercially available and comprise polyglucosamine, humic and fulvic acids and carboxylic acids. The researchers applied these to the cv. Orange Rubis. Due to the rapid fruit ripening caused by this, 73 % of the fruits could be harvested in the first harvest as opposed to 43 % in the control treatment (54). Over the course of the 2 years of research, the fruits' power to combat oxidative stress was also enhanced. In one of the 2 years of the assessment, fruits from plants treated with Ergostim® showed more breadth than fruits from plants treated with other plant biostimulants and control plants. On the other hand, the fruit's length, thickness, hardness, colour, brightness and weight did not alter in any noticeable ways (55). Using *Ascophyllum nodosum* extract (AE) in orange orchards improved total soluble solids levels and decreased titratable acidity, all while advancing fruit harvest by as much as seven days. At an applied rate of 0.30 %, a 15 % boost in productivity was noted (56, 57). When 2 cherry cultivars, Sweetheart and Skeena were grafted on cv. Gisela 6, *Ascophyllum nodosum*-based extract (AE) was applied and the cracking index decreased. Furthermore, the fruits had increased in breadth, weight, diameter, pH and wax content. On the other hand, no changes in fruit production or nutritional qualities were noted (58). An abundance of peptides, amino acids and minerals were found in the plant biostimulant that was made from decomposing chicken feathers. It was applied to banana roots by fertigation at a 20 % concentration or sprayed on the leaves at a 5 % concentration. The mature fruits exhibited increased quantities of proteins, amino acids, reducing sugars, phenolics and flavonoids following these administrations, which were applied 15 days after the seedlings were transplanted. Notably, it was shown that root treatment was more successful than foliar spray at bringing about these modifications and encouraging increased yield (59).

Genetic basis of mitigation using biostimulants

To fully understand how biostimulants work and how they affect plant growth, scientists need to explore the mechanisms behind their biological activity. This involves identifying the active compounds in biostimulants and figuring out how they impact plant productivity. Various advanced techniques like microarrays, metabolomics, proteomics and transcriptomics are used to study changes in gene expression when biostimulants are applied to plants (66). Further research is necessary to understand how these biostimulants affect the entire genome or transcriptome of plants, especially under stress conditions like drought or disease. Signaling molecules play a crucial role in how plants respond to their environment. These molecules are produced in response to external cues, move to their target sites, bind to specific receptors and trigger a series of cellular responses (67). This process often involves secondary messengers like ions, sugars and certain proteins, which further propagate the signal inside the cell. The type of signaling depends on whether the molecule is water-soluble or fat-soluble, with water-soluble molecules typically acting at the cell membrane and fat-soluble ones within the cell's cytoplasm. Signaling molecules in plants are not as straightforward as the "lock and key" model seen with enzymes and their substrates (68). Instead, they are thought to have a specific affinity for their receptors and their interactions can be cooperative.

Some biostimulants may contain bioactive compounds that influence these signaling pathways, such as certain amino acids and peptides. These compounds can regulate various aspects of plant growth and development, including how plants respond to stress, how leaves form and how roots grow (69). Protein hydrolysates, which are proteins broken down into smaller peptides, have also been shown to affect plant growth and immunity. For example, protein hydrolysates from soybean and casein have been found to enhance the immune response in grapevines against a common pathogen. Additionally, some proteins may contain hidden peptide sequences, known as cryptides, which have their own biological activities and can trigger plant defense mechanisms. Small molecules like amino acids, sugars and fatty acids also play important roles in plant signaling. These substances can act directly as signaling molecules or influence hormone activity, helping plants cope with stress and regulate growth processes. For instance, amino acids in biostimulants are easily absorbed by plants and can help in various ways, such as regulating water balance, controlling stomatal opening, and detoxifying harmful substances. Sugars and fatty acids can also serve as signaling molecules, coordinating with plant hormones to enhance growth and yield (70).

The genetic basis of mitigation using biostimulants involves understanding how these substances interact with plant genes to enhance stress resistance and overall plant health. Biostimulants can trigger specific genetic pathways that regulate the production of antioxidants and stress-responsive proteins, which play crucial roles in the oxidant-antioxidant system. For instance, when plants are exposed to oxidative stress, biostimulants may activate genes associated with the synthesis of antioxidant enzymes, such as superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPX). These enzymes help convert harmful reactive oxygen species (ROS) into less harmful molecules, thus protecting the plant from damage. Moreover, biostimulants can influence the expression of genes involved in the ascorbate-glutathione cycle, enhancing the plant's ability to scavenge hydrogen peroxide (H_2O_2) and other ROS. Additionally, biostimulants may promote the upregulation of genes associated with signaling pathways that respond to environmental stresses, facilitating plant priming. This preconditioning effect allows plants to mount a more robust defense against future abiotic and biotic stressors by enhancing their physiological and biochemical responses. Research has indicated that various beneficial microorganisms found in the rhizosphere can also play a role in activating genetic pathways that strengthen plant defenses. The interplay between biostimulants and plant genetics not only enhances the ability of plants to cope with oxidative stress but also supports their overall growth and productivity. Understanding these genetic mechanisms can provide valuable insights into optimizing the use of

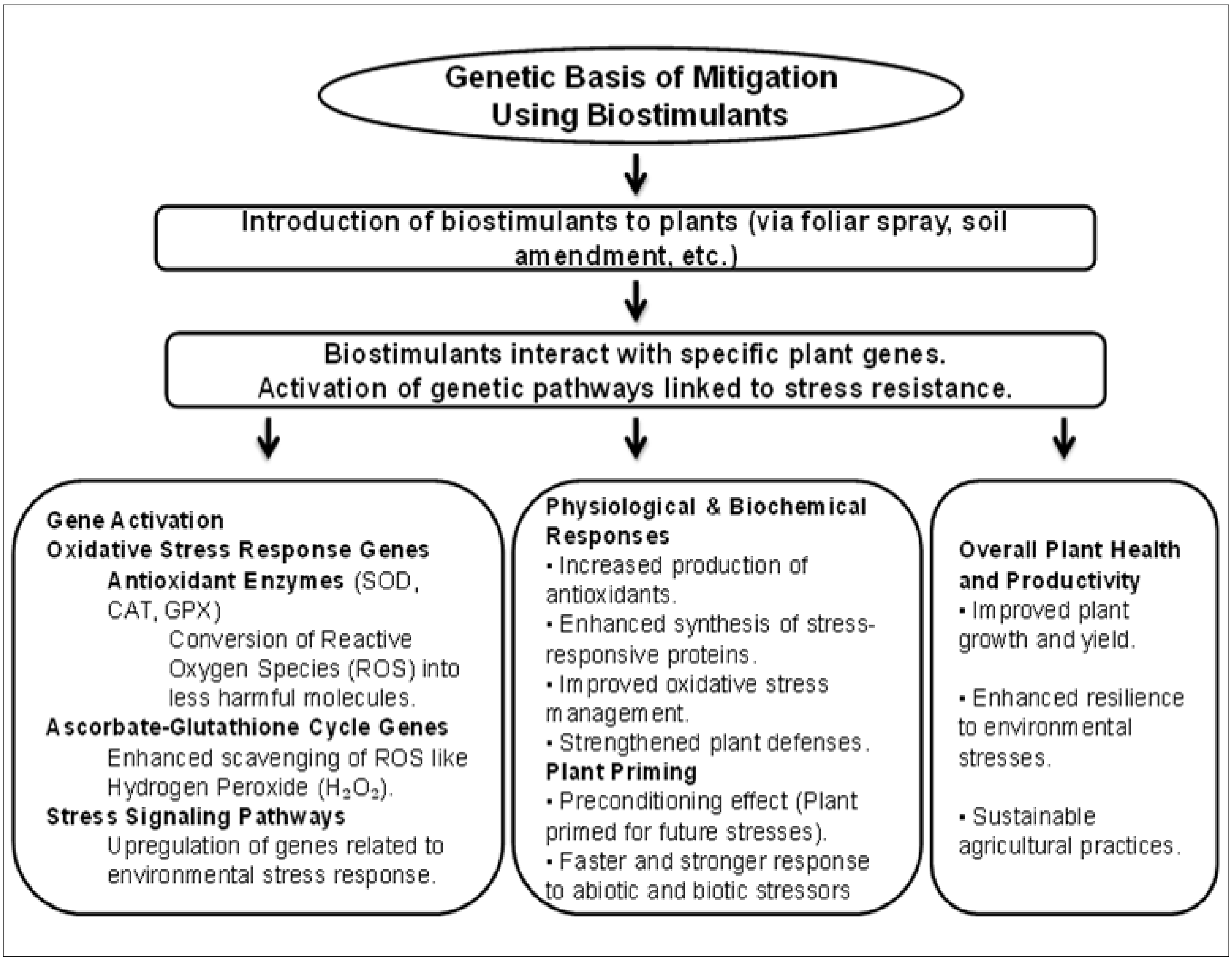

Fig. 4. Genetic basis of mitigation using biostimulants.

biostimulants for sustainable agriculture and improved crop resilience (71, 72).

Conclusion and future prospects

Abiotic stresses compromise the quality and production of crops by disrupting their physiology, growth and metabolic activities. Biostimulants provide an environmentally acceptable alternative by regulating the production of phytohormones, osmolytes, organic acids and nutrient intake as well as by enhancing antioxidant defences and genes associated with stress tolerance in the root microbiome. To properly understand this process, more molecular analysis is required. To tackle food security issues, we must develop stress-resistant biostimulants and standardize international regulations for their use. The absence of consistency in the current biostimulant legislation calls for a unified worldwide framework. Single-strain applications are effective from a strain perspective, but microbial consortiums have potential. The effectiveness of bioactive substances in improving the performance of microbial consortiums is shown in a recent study, highlighting their group action. Single strains may struggle in difficult circumstances, hence multi-strain microbial consortia are a useful strategy for sustainable agriculture under abiotic stress. In the midst of the COVID-19 epidemic, there are risks to global health and food security. All industries, including agriculture, are being studied in relation to COVID-19's effects (73). The market for biostimulants was valued at $3.34 billion in 2022 and is anticipated to rise to $3.69 billion in 2023 and $7.97 billion by 2030, according to projections. The COVID-19 pandemic has highlighted the importance of biostimulants in sustainable agriculture, prompting governments in major agricultural countries to protect their industries and boost crop yields.

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Authors' contributions

M conceived the study, contributed to its design and coordinated the research activities. RS participated in the experimental design, conducted the literature review and drafted the manuscript. RK carried out the data collection and assisted with statistical analysis. PB provided technical guidance and contributed to the critical revision of the manuscript. NT was responsible for the analysis and interpretation of the results. NS assisted with data interpretation and manuscript formatting. PS contributed to the study design and provided logistical support. All authors read and approved the final manuscript.

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