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Sustainable fruit cultivation using biostimulants: Improving nutrient efficiency, defense, and productivity

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Abstract

The increasing challenges posed by climate change and environmental stressors have led to a noticeable decline in fruit yield and quality, along with a surge in pest and disease incidence. This, in turn, has encouraged the overuse of chemical fertilizers and pesticides, which degrade soil health and leave harmful residues. To address these concerns, biostimulants have emerged as a sustainable alternative, offering multifaceted benefits without posing environmental risks. Biostimulants, encompassing natural substances and beneficial microorganisms, act by enhancing nutrient absorption, improving stress resilience, and promoting plant growth and productivity. They do not directly supply nutrients but instead stimulate natural plant processes to improve nutrient use efficiency, tolerance to abiotic stress, and crop quality. This review covers major classes of biostimulants including humic substances, seaweed extracts, chitosan, protein hydrolysates, and microbial inoculants such as plant growth-promoting bacteria (PGPB) and fungi (PGPF). These microbial agents enhance root development, increase nutrient availability, modulate plant hormones, activate antioxidant defense systems, suppress pathogens through the production of bioactive compounds, improve soil microbiota and plant immunity. The application of these biostimulants in various fruit crops have shown improved fruit size, firmness, color, nutrient content, yield and extended postharvest life. Moreover, integrating biostimulants into fruit production system offers a sustainable approach to mitigating the adverse effects of changing climatic dynamics. By reducing reliance on chemical inputs and enhancing plant resilience, biostimulants significantly contribute to the sustainability and profitability of horticulture. This review explores the different categories of biostimulants used in fruit cultivation and highlights their mechanisms in improving nutrient uptake, stress tolerance, and disease resistance.

Keywords: Biostimulants, humic substances, chitosan, beneficial microoragnisms, sustainable horticulture

Introduction

Biostimulants are those microorganisms or substances which are applied to plants in order to improve their nutrient uptake efficiency, enhance plant's tolerance to abiotic stress and boost their quality traits (du Jardin, 2015) [16]. These substances enhance plant nutrition, regardless of their own nutrient content. The term 'biostimulant' was introduced by horticultural experts to describe such substances which enhance plant growth without functioning as nutrients, or soil conditioners (du Jardin, 2015) [16]. Plant biostimulants can be broadly categorized into natural compounds such as amino acids, humic acid, fulvic acid, protein hydrolysates, seaweed derived extracts. They also include biofertilizers like rhizobium, trichoderma species, arbuscular mycorrhiza and non-mycorrhizal fungi (Rouphael *et al.*, 2015) [57]. These compounds augment the activity of antioxidant enzymes and therefore aim to improve plant's stress resilience and overall productivity. Plants are increasingly facing stresses like salinity, drought, high and low temperature, nutrient shortages which have further been intensified by changing climatic dynamics. Also, because of the rising population and increased demand of food, we have started to heavily rely upon fertilizers, pesticides and other chemical inputs which has led to degradation of soil quality and health, deteriorated microbial diversity and heightened ecological concerns, therefore, highlighting the need for sustainable approaches. In this regard, biostimulants offer a promising solution by helping crops better cope up with environmental stresses, reduce the need for chemicals, lower the environmental footprints while also increasing the nutrient uptake of plants. In fruit crops, where long life cycles and complex developmental stages make them particularly vulnerable to prolonged stress exposure, biostimulants offer promising advantages. They not only promote root development, root architecture, nutrient absorption and water uptake efficiency but also activate antioxidant defense systems, improve osmotic regulation, membrane stability, maintain ion homeostasis and modulate phytohormonal balances, all of which contribute to improved stress tolerance and crop performance (Calvo *et al*., 2014) [9]. These substances have been further found to improve flowering and fruit quality which includes enhanced TSS, firmness and colour even under stressful conditions. The application of biostimulants is known to improve the nutritional value of edible plant parts as well, by promoting the synthesis of beneficial secondary metabolites (Teklić *et al*., 2021) [62], while also take care of the post harvest health and life of the fruit crops. Thus, biostimulants have emerged as eco-friendly alternatives that can improve stress tolerance, nutrient use efficiency and overall fruit quality without posing environmental risks.

Biostimulants can act as complimentary agents to fertilizers by enhancing nutrient absorption. Microbial biostimulants, particularly beneficial fungi and bacteria, play a key role in enhancing soil health and plant vitality by altering microbial communities around roots. These organisms can accelerate organic matter breakdown and suppress harmful microbes, indirectly aiding plant growth. Common fungal species like *Trichoderma* and *Glomus* enhance nutrient absorption, while bacterial genera such as *Bacillus*, *Pseudomonas*, and *Enterobacter* improve nutrient availability and stress tolerance. Although they don't directly supply nutrients, these microbes boost plant metabolic functions, facilitating more efficient nutrient uptake and supporting overall crop performance (Sunitha *et al*., 2022) [61]. Beneficial microorganisms enhance plant resilience to biotic and abiotic stresses through various mechanisms. They improve nutrient uptake, produce phytohormones like auxins and gibberellins, and induce systemic resistance against pathogens. Besides, many beneficial bacteria also produce various bioactive compounds that contribute to disease suppression. A growing number of farmers are incorporating biostimulants to enhance crop growth and yield. These are commonly applied through foliar sprays or added to the soil and are often most effective when used in combination with fertilizers.The integration of biostimulants into agricultural practices represents a promising strategy for enhancing crop productivity and resilience. By improving nutrient use efficiency, bolstering stress tolerance, and reducing reliance on chemical inputs, biostimulants contribute to more sustainable and environmentally friendly farming systems. This review will explore the various types of biostimulants utilized in fruit crops and examine their roles in enhancing fruit quality and yield, as well as their effectiveness in managing diseases, pests, and adapting to changing environmental conditions and the stresses that prevails as a result.

Humic Substances (HS)

Humic substances (HS), which include humic and fulvic acids, are complex organic compounds that originate from the microbial and chemical breakdown of plant, animal, and microbial residues. They represent a significant portion of the Earth's surface organic carbon and play a crucial role in regulating ecological and soil processes. HS enhance soil structure, influence the cycling of carbon and nitrogen, and affect the mobility and fate of contaminants and heavy metals. Their application in agriculture, especially in fruit crops, has been associated with improvements in both soil fertility and plant resilience (Canellas *et al*., 2015) [10]. Numerous studies have demonstrated that HS positively influences plant growth by enhancing both primary and secondary metabolic processes. At the physiological level, humic substances stimulate key nitrogen assimilation enzymes such as nitrate reductase (NR), glutamate dehydrogenase (GDH), and glutamine synthetase (GS), thereby improving nutrient metabolism and uptake efficiency (Hernandez *et al*., 2015) [27]. Besides, humic acids (HA) have been shown to increase the activity of antioxidant enzymes superoxide dismutase, catalases, peroxidase, ascorbate peroxidase, peroxidases, mitigate oxidative stress, and modulate the levels of plant hormones including IAA, brassinosteroids (BR), and stress-related phytohormones like ABA, jasmonic acid, and salicylic acid. These biochemical changes help maintain photosynthetic efficiency and osmotic balance under stress conditions such as salinity. A meta-analysis by Rose *et al*. (2014) [56] revealed that exogenous application of HS resulted in an average 22% increase in both shoot and root biomass across various plant species. These findings support the role of HS in enhancing plant vigor through improved nutrient use efficiency and stress mitigation mechanisms. Furthermore, HS can induce structural modifications in plant roots and shoots, promoting overall physiological adaptation and stress tolerance. A field trial conducted by Rajan *et al*., 2018 [53] on mango cv. Alphonso nursery grafts showed that both the frequency and concentration of humic acid drenching significantly improved growth traits such as plant height, leaf area, root development, and dry matter. The best results were observed when humic acid was applied four to five times**,** particularly at 7.5 ml and 10 ml concentrations**,** indicating a strong positive correlation between higher application rates and enhanced plant growth. The combined application of biochar and humic acid has been shown to enhance soil microbial balance, improved enzyme activities like urease, catalase, phosphatase in the soil, promoting a favorable rhizosphere environment and leading to suppressed pathogenic *Fusarium* activity, thereby boosting apple seedling growth, mitigating replant disease effects and enhancing antioxidant enzymatic activity in both leaves and roots (Liu *et al*., 2024) [37]. In organic *Fragaria* × *ananassa* (cv. Onda), prolonged foliar application of humic and fulvic acids significantly enhanced photosynthetic activity and fruit quality, reducing misshapen and rotten fruits and increasing sugar content, likely due to systemic physiological benefits rather than direct nutrient supplementation (Neri *et al*., 2002) [46]. Applying biostimulants such as humic and fulvic acids, seaweed extracts, or nitrogen-fixing bacterial mixes have shown to promote early root and shoot development in northern highbush blueberry (*Vaccinium corymbosum* L.), with humic substances thus enhancing root biomass and nutrient availability (e.g., P and Zn), while seaweed extracts contribute to increased plant height and vigor, highlighting their beneficial role during plant establishment, although long-term effects on yield and quality remain variable and context-dependent (Bryla *et al*., 2023) [8].

Currently, most agricultural HS are sourced from non-renewable materials such as peat, coal, and mineral deposits. However, growing concerns over sustainability have shifted focus toward renewable sources like compost and vermicompost (Sunitha *et al*., 2022) [61]. Utilizing organic waste materials to produce HS offers a promising, eco-friendly alternative to conventional extraction methods, aligning with the goals of sustainable horticulture. Moreover, sodium humate derived from coal has been found to significantly increase crop growth, yield, and nutrient uptake, particularly in calcareous soils. Humic acids play a crucial role in releasing nutrients bound to soil particles, viz-a-viz their ability to dissociate phosphorus from aluminum complexes, thereby improving phosphorus availability for plant uptake. Also, their strong chelating ability enhances the solubility and uptake of micronutrients by forming stable complexes, improving overall nutrient efficiency even under stressful alkaline conditions (Kakar *et al*., 2018) [29].

Seaweed Extracts

Seaweeds, classified as brown, red, or green marine macroalgae, are widely used in organic horticulture, especially brown types like *Ascophyllum*, *Fucus*, and *Laminaria* (Sunitha *et al*., 2022) [61]. Their extracts contain a rich mix of trace elements, amino acids, vitamins, and growth-promoting hormones such as auxins, cytokinins, gibberellins, ethylene, and polyamines. When applied at low concentrations, seaweed-based biostimulants can trigger enhanced plant growth, improved flowering and fruit development, increased nutrient content, and extended postharvest shelf life, making them valuable tools for improving crop productivity and stress resilience (Rana *et al*., 2023) [54]. Seaweed extracts derived from various marine algae species have shown significant promise in improving growth, yield, and quality in fruit crops, while also offering protection against certain diseases. In apples, commercial formulations of *Ascophyllum nodosum* extracts have effectively reduced alternate bearing (Spinelli *et al*., 2009) [60]. This indicates a potential role of seaweed biostimulants in stabilizing production cycles in perennial fruit trees. Foliar application of seaweed-extract-based fertilizers significantly enhances nutrient uptake, photosynthetic efficiency, and enzyme activity in 'Fuji' apple trees, while also improving fruit quality traits such as sugar-acid balance, mineral content, vitamin C, and phytohormone levels, collectively promoting better flavor, nutritional value, and overall fruit development (Yang *et al*., 2023) [67]. Application of seaweed extracts has been found to enhance yield and nutritional quality of 'Golden Delicious' apples by increasing vitamin C, total phenols, and protein content, while also improving leaf nutrient status, antioxidant activity, chlorophyll content, and relative water content, ultimately boosting photosynthesis and overall tree performance (Mousavi *et al*., 2024) [45]. In grapes, the use of *Ascophyllum nodosum* extracts has been linked with enhanced nutrient uptake, particularly copper, potassium, and calcium, which contributes to improved berry size, weight, firmness, and overall yield. Furthermore, uniformity in ripening was observed, which is crucial for quality consistency and marketability (Mancuso *et al*., 2006) [42]. Foliar spraying with a combination of amino acids and seaweed extract has been shown to significantly enhance grape yield, berry weight, and overall fruit quality (Khan *et al*., 2012) [31]. Besides, foliar application of *Ascophyllum nodosum*-based seaweed extract at specific phenological stages has significantly enhanced pear fruit diameter, weight, cell number, seed number, and total yield, without adversely affecting fruit maturity or vegetative growth, demonstrating its potential to improve both fruit quality and productivity under commercial orchard conditions (Colavita *et al*., 2011) [11]. A study demonstrates that foliar application and fruit dipping of ‘Allison’ kiwifruit in seaweed extract significantly improves fruit size, weight, yield, and quality parameters such as soluble solids content, sugar levels, and ascorbic acid. Further, this treatment enhances shelf life and reduces postharvest losses, positioning seaweed extract as a promising biostimulant alternative to synthetic growth regulators when applied during the early stages of fruit development (Rana *et al*., 2023) [54]. Moreover, Foliar application of seaweed extract positively influences the growth, mineral uptake, yield, and fruit quality of ‘Sweet Charlie’ strawberries by enhancing the plant’s vegetative traits, improving nutrient content, and increasing fruit firmness, sweetness, and overall productivity (El-Miniawy *et al*., 2014) [20]. Seaweed extracts have proven beneficial in citrus crops like oranges, especially under drought stress conditions. Treatments have shown to improve vegetative growth and fruit quality by increasing parameters such as fruit weight, sugar content, and total soluble solids, underscoring their role in stress mitigation and quality enhancement (Kamel 2014) [30]. In bananas and papayas, red seaweed species such as *Ochtodes secundiramea* and *Laurencia dendroidea* demonstrated antifungal properties by effectively inhibiting anthracnose, a common and destructive postharvest disease (Machado *et al*., 2014) [40]. Therefore, the diverse applications of seaweed-based biostimulants across various fruit crops highlights their significant role in enhancing yield, improving fruit quality, extending shelf life, and boosting resilience against environmental stresses and diseases, thereby offering a sustainable alternative to conventional agricultural inputs.

Chitosan

Chitosan is a linear polysaccharide and the deacetylated form of chitin, which is derived from insect exoskeletons, crustacean shells, and fungal cell walls (Sunitha *et al*., 2022) [61]. Although it is obtained naturally, it can also be synthesized industrially (Attia *et al*., 2021) [2]. It acts as a biostimulant with numerous benefits for plant health and productivity. Chitosan induces several defensive genes in plants, such as pathogenesis-related genes like glucanase and chitinase (Pichyangkura *et al*., 2015) [51]. It also activates various enzymes in the reactive oxygen species scavenging system, including superoxide dismutase, catalase, and peroxidase, offering protection against fungi, bacteria, viruses, salinity, drought and water stress conditions (Pichyangkura *et al*., 2015) [51]. The stimulation of enzyme activities involved in detoxifying reactive oxygen species implies that hydrogen peroxide and nitric oxide play roles in chitosan signaling, while chitosan may also interact with chromatin to directly regulate gene expression; moreover, recent advancements include the development of chitosan nanoparticles as an efficient delivery system for fertilizers, pesticides, herbicides and micronutrients, supporting balanced and sustained nutrient release to enhance crop growth (Malerba *et al*., 2016) [41]. Besides, chitosan has been utilized both as a biostimulant to promote plant growth and enhance tolerance to abiotic stress, and as an agent to induce resistance against pathogens. Further, it is employed in seed coating, foliar treatments, and postharvest fruit coatings to prevent decay and extend shelf life (Sunitha *et al*., 2022) [61]. A study evaluating chitosan-based edible films incorporated with turmeric and green tea extracts found out significant enhancement of antifungal activity against *Botrytis cinerea* in strawberry, while green tea improved the antioxidant potential of the films. The inclusion of both extracts also increased the mechanical strength of the films and contributed to prolonged shelf life of postharvest strawberries without negatively affecting their sensory qualities. Remarkably, turmeric extract was explored for the first time in food packaging, demonstrating its potential as a complementary antioxidant agent alongside green tea extract (Yang *et al*., 2022) [66]. Research suggests that chitosan-based nanopesticides offer a promising strategy for managing trunk diseases in grapevines due to their dual role in antimicrobial action and plant growth promotion. As a widely used and human-safe biomaterial in nanotechnology, chitosan can be formulated into nanocomposites that function effectively as biocides, disease suppressants, and growth enhancers, highlighting its potential as a sustainable alternative in viticulture disease management (Singh *et al*., 2022) [59]. Chitosan and beeswax have been reported to form a thin film barrier on plum fruit peel, effectively covering the stomata. This coating reduces moisture loss by minimizing transpiration and also lowers the respiration rate, thereby extending the fruit's shelf life (Gunaydin *et al*., 2017) [24]. Also, foliar application of chitosan at the full bloom stage (specifically 50 days after bloom) has been shown to significantly enhance yield and fruit quality in the 'Early Grande' peach cultivar. This treatment has led to increases in fruit weight, volume, firmness, titratable acidity, and ascorbic acid content, while improving juice pH and reducing disease incidence, making it more effective compared to applications at other growth stages (Sajid *et al*., 2020) [58]. Chitosan coatings have been shown to effectively extend the shelf life and preserve the quality of postharvest mango fruits. Application of chitosan inhibits decay, controls weight loss, and reduces postharvest diseases by lowering total bacterial and mold counts. Chitosan treatments help retain quality attributes such as vitamin C, titratable acidity, sugars, ash, and protein content during storage. Also, coating mangoes with a 1000 ppm chitosan solution, combined with zip-bag packaging at low temperatures, has shown superior performance in prolonging shelf life while maintaining fruit quality (Parvin *et al*., 2023) [49].

Protein Hydrolysates (PH)

PHs are a key class of biostimulants composed of amino acids, peptides, oligopeptides formed primarily through enzymatic or chemical breakdown, partial or complete hydrolysis of proteins sourced from plants, animals or agro-industrial residues (Zulfiqar *et al*., 2020) [59]. These compounds have shown promising results in enhancing seed germination, crop yield, and produce quality across various horticultural and field crops. PHs play a beneficial role in helping plants cope with abiotic stresses such as salinity, drought, and heavy metal toxicity, contributing to improved stress resilience and overall plant health. Protein hydrolysates enhance soil fertility and stimulate microbial activity, indirectly supporting plant development and yield. Their direct influence includes hormone-like effects and regulation of primary and secondary metabolic pathways by modulating key enzymes and genes involved in nitrogen assimilation and the TCA cycle. Besides, certain amino acids in these hydrolysates exhibit chelating abilities, thereby, helping to mitigate heavy metal stress and facilitate the uptake and mobility of essential micronutrients (Sunitha *et al*., 2022) [61]. These substances can be applied either via foliar spraying or integrated into drip irrigation systems, with amino acids being readily absorbed through both the foliage and root systems of plants (Ertani *et al*., 2018) [21]. A field study on wine grape cv. Corvina demonstrated that foliar applications of animal- and plant-derived protein hydrolysates (PHs), such as those from soybean, casein, and lupin, enhanced yield, fruit quality (e.g., °Brix and anthocyanin content), and water stress tolerance. Results varied depending on biostimulant type and concentration, with soybean and casein showing the most significant improvements in yield and stress mitigation (Boselli *et al*., 2015) [6]. Lachhab *et al*., 2014 found that hydrolysates derived from soybean and casein can activate multiple defense mechanisms in grapevines. These include the stimulation of calcium signaling, the production of pathogenesis-related proteins, and the induction of the phenylpropanoid pathway, all of which contribute to enhanced resistance. As a result, treated plants showed improved ability to defend against pathogens such as *Plasmopara viticola* and *Botrytis cinerea*. These hydrolysates are rich in low molecular weight peptides capable of influencing key biological processes, including hormonal regulation and immune responses (Phelan *et al*., 2009) [50]. Casein and soybean hydrolysates, in particular, have gained prominence for their natural antioxidant and antimicrobial properties, making them suitable as functional ingredients in food and pharmaceutical formulations (Kumar *et al*., 2013) [33]. A study on potted kiwifruit plants revealed that foliar application of protein hydrolysates, derived from enzymatically processed peptone, especially at lower molecular weight fraction enhanced shoot and root growth more effectively than traditional urea treatments, improved biomass accumulation (Quartieri *et al*., 2002) [52]. Application of hydrolyzed feather waste, a by-product of poultry processing, has been shown to significantly enhance banana crop performance. This treatment led to a reduction in harvesting time by 28 days and increased the number of hands per bunch by 10%, fingers per hand by 24%, and overall bunch weight by 16% compared to untreated controls. The improvements are attributed to elevated chlorophyll and reducing sugar contents in the plants. These findings suggest that feather degradation products can serve a dual purpose: acting as bioenhancers to reduce fertilizer usage in horticulture and providing an effective solution for poultry waste management (Morales-Pajan and Stall, 2003) [44]. Also, in a field trial conducted by Gaurav and Jadav 2013, root and foliar application of chicken feather derived PH has led to early flowering in banana, while also increasing the chlorophyll content, nutrient and proline levels. Plant-derived protein hydrolysates (PHs) are favored over animal-based counterparts due to their superior agronomic benefits. These biostimulants exert both direct and indirect positive effects on crops. Directly, they exhibit auxin- and gibberellin-like activities, influencing plant metabolic processes. Indirectly, PHs enhance root development, leading to an increased root surface area, which improves nutrient and water uptake efficiency (Colla *et al*., 2015) [12].

Microorganisms as Biostimulants

Beneficial microorganisms, including beneficial fungus called as Plant Growth-Promoting Fungi (PGPF) and beneficial bacteria called as Plant Growth-Promoting Rhizobacteria (PGPR), are increasingly utilized as biostimulants in horticulture. *Trichoderma* species, a type of PGPF, contribute to plant health by promoting growth and offer protection against certain pathogens. Various mychorhizal and non-mychorhizal fungi are also included in this category. Besides, PGPR includes genera *Azotobacter*, *Rhizobium*, and *Azospirillum*, which are known for their nitrogen-fixing capabilities, which convert atmospheric nitrogen into forms accessible to plants, thereby reducing the need for chemical fertilizers (Attia *et al*., 2022; McNear *et al*., 2013) [1]. These microorganisms enhance plant growth through various mechanisms, including nitrogen fixation, phosphate solubilization, and the synthesis of phytohormones. The application of these microorganisms not only supports sustainable agricultural practices but also enhances soil fertility and plant resilience. Many microbial symbionts serve as effective biofertilizers by releasing additional nutrients to plants through synergistic mechanisms. For instance, nitrogen fixation is facilitated by bacteria such as *Mesorhizobium loti*, *Rhizobium etli*, *Azotobacter vinelandii*, and *Azospirillum brasilense*. Phosphate solubilization is carried out by organisms including arbuscular mycorrhizal fungi, *Azospirillum* spp., *Bacillus* spp., and *Pseudomonas* spp. Moreover, cellulolytic activity is provided by microbes like *Aspergillus* spp., *Trichoderma* spp., *Bacillus* spp., and *Penicillium* spp., while soil acidification occurs through the actions of *Bacillus* spp. and *Arthrobacter* spp., and siderophore production is mainly associated with *Pseudomonas* spp. (Orozco-Mosqueda *et al*., 2021) [48]. Enhancing plant resilience against climate change-related stresses offers a sustainable approach to ensuring food security without significantly expanding agricultural land, with microbial biostimulants emerging as a highly promising strategy to achieve this objective (Yakhin *et al*., 2017) [65]. The integration of microbial biostimulants into agricultural practices can help preserve the ecological balance of agro-ecosystems while reducing dependence on chemical pesticides and heavy metal treatments.

Beneficial Fungi

Beneficial fungi interact with roots of plants and offer symbiotic association, wherein both are benefitted from each other and are rightly called as Plant growth promoting fungi (PGPF). Beneficial fungi, including species such as *Trichoderma*, yeasts, mycorrhizal fungi endophytes, and certain avirulent or hypovirulent strains of pathogens, play a significant role in enhancing plant health and growth. Mycorrhizal fungi, a diverse group, form symbiotic relationships with the roots of most terrestrial plants, facilitating improved nutrient and water uptake, thereby bolstering the plant's resilience to various stressors. Among these, arbuscular mycorrhizal fungi (AMF) are particularly notable for their widespread association with numerous plant species (du Jardin, 2015) [16]. Glomeromycota species penetrate root cortical cells, forming structures known as arbuscules, which are pivotal for nutrient exchange (Behie and Bidochka, 2014) [3]. The symbiotic relationship with AMF enhances nutrient absorption, optimizes water use efficiency, and strengthens the plant's defense mechanisms against both biotic and abiotic stresses. Given these advantages, there is growing interest in leveraging mycorrhizal fungi to promote sustainable agricultural practices. Fungal-based products, particularly those containing arbuscular mycorrhizal fungi (AMF), are recognized as biostimulants due to their ability to enhance plant nutrient efficiency, stress tolerance, crop yield, and product quality. Apart from serving as bistimulants, PGPF also function as biofertilizers, biocontrol, agents and plant growth regulators. Studies have demonstrated that arbuscular mycorrhizal fungi (AMF) can significantly reduce disease severity in strawberry plants caused by pathogens such as *Rhizoctonia fragariae*, *Fusarium oxysporum*, and *Alternaria alternata*. These fungi enhance plant growth parameters, including fresh and dry weight, and increase biochemical constituents like total phenolic content, antioxidant activity, and phosphorus levels. The effectiveness of AMF varies with the specific fungal species and the pathogen involved, highlighting the potential of AMF in integrated disease management strategies for strawberries (Demir *et al*., 2023) [15]. Arbuscular mycorrhizal fungi (AMF) establish symbiotic relationships with plant roots, enhancing the host's resilience to various abiotic stresses, including heat, salinity, drought, heavy metal toxicity, and extreme temperatures. These fungi facilitate the uptake of essential nutrients, such as phosphorus, thereby improving plant growth and yield under both normal and adverse conditions. AMF can modulate the plant's stress response mechanisms by upregulating tolerance pathways and preventing the downregulation of critical metabolic processes. Consequently, AMF serve as natural bio-fertilizers, strengthning plant adaptability to environmental changes. Further research into AMF-mediated enhancement of crop quality and productivity is warranted to fully harness their potential in sustainable agriculture (Begum *et al*., 2019) [4]. However, large-scale application of AMF faces challenges primarily because of the fungi's obligate biotrophic nature, making *in vitro* propagation complex and labor-intensive (Dalpé and Monreal, 2004) [13]. Besides, limited understanding of host specificity and the dynamics of mycorrhizal populations within agroecosystems further complicates their effective utilization in sustainable agriculture.

Trichoderma species are widely recognized for their efficacy in biologically controlling various phytopathogens, including *Fusarium oxysporum*, *Rhizoctonia solani*, *Armillaria mellea, and Chondrostereum purpureum*. These fungi function as plant growth-promoting fungi (PGPF), producing secondary metabolites that protect plants from soil-borne diseases and enhance growth, development, and yield (El-Komy *et al*., 2015) [18]. Trichoderma species are increasingly recognized as effective biocontrol agents, offering a sustainable alternative to chemical fungicides. These fungi exhibit antagonistic properties against a broad spectrum of phytopathogens, thereby promoting crop growth and playing a pivotal role in advancing sustainable agricultural practices (Liu *et al*., 2016) [36]. Trichoderma species function as biostimulants by enhancing crop growth and nutrient uptake. They aid plants in withstanding environmental stresses, such as salinity and drought, by promoting growth and altering gene expression in roots and shoots. The fungal mycelium secretes compounds, including auxins, small peptides, and volatile organic compounds, that increase root branching, thereby improving nutrient and water acquisition. Recent studies indicate that Trichoderma activates mitogen-activated protein kinase 6 (MPK6), transcription factors, and DNA processing proteins, which are promising targets for developing more efficient biostimulant products (López-Bucio *et al*., 2015) [39]. Trichoderma species, such as *T. harzianum*, *T. atroviride*, and *T. virens*, are widely utilized as biocontrol agents (Yassin *et al*., 2021) [58] due to their adaptability to diverse environmental conditions (Kthiri *et al*., 2021). Another strain, *T. asperellum* is known to not only effectively suppresses plant diseases but also enhances crop growth (El-Komy *et al*., 2016) [19]. The application of *Trichoderma asperellum* strain 6S-2 as a fungal fertilizer has been shown to alleviate apple replant disease (ARD) by promoting plant growth and modifying the soil microbial community. In greenhouse and pot experiments, as well as field trials, this treatment enhanced the growth of *Malus hupehensis* Rehd seedlings and increased branch elongation in young apple trees. Significant changes in soil microbiota included a significant rise in beneficial genera such as *Trichoderma*, *Bacillus*, and *Streptomyces*, coupled with a reduction in harmful fungi like *Fusarium* and *Cryptococcus*. Also, there were increases in the bacteria: fungi ratio and soil enzyme activities. Alterations in root exudate composition, such as elevated levels of alkenes, ethyl ethers, and citrullines, correlated positively with *Trichoderma* abundance, while decreases in aldehydes, nitriles, and naphthalenes were associated with reduced *Fusarium* presence. Furthermore, improvements in soil nutrients, including ammonium nitrogen, nitrate nitrogen, available phosphorus, available potassium, organic matter, and pH levels were observed, collectively contributing to the mitigation of ARD symptoms (Wang *et al*., 2021) [63]. In a study examining the effects of *Trichoderma* strains T22, TH1, and GV41 on strawberry plants, remarkable enhancements in plant growth and fruit yield were observed. Additionally, there was a selective accumulation of anthocyanins and other antioxidants in fully ripened fruits. Proteomic analyses indicated significant changes in protein expression related to stress responses, nutrient uptake, protein metabolism, energy pathways, and secondary metabolism, shedding light on the increases in specific fruit metabolites. Bioinformatic evaluations identified a central network of interacting proteins, suggesting coordinated modulation of various physiological processes following *Trichoderma* inoculation. Furthermore, the application of *Trichoderma* led to increased levels of enzymes such as squalene synthase and β-amyrin synthase, which are involved in the biosynthesis of sesquiterpenoids and triterpenoids—compounds known to deter herbivores and attract their predators (Lombardi *et al*., 2020) [38]. In greenhouse trials, applying a conidial suspension of *Trichoderma asperellum* to the aerial parts of strawberry plants, either before or after inoculation with *Colletotrichum gloeosporioides*, resulted in reduced leaf infection severity compared to untreated controls. Further, *T. asperellum* treatments enhanced plant growth, including improvements in rosette diameter, aerial part length, root length, and fresh weights of both aerial and root parts, leading to increased fruit yields per plant (El Kaissoumi *et al*., 2023) [17]. A study investigated the protective effects of endophytic *Trichoderma* species against *Armillaria mellea* infection in strawberry (*Fragaria* × *ananassa*), finding that pre-colonization with *T. atrobrunneum* can effectively protect plants from *A. mellea* infection (Rees *et al*., 2022) [55]. Nujhet *et al*., onstrated that soaking mangoes in a *Trichoderma asperellum* KUFA 0042 spore suspension significantly reduced lesions caused by *Lasiodiplodia theobromae* and *Colletotrichum gloeosporioides*. Besides, applying a formulation containing spores of *T. asperellum* strain DGA01 effectively inhibited black rot development in pineapple fruits inoculated with *Thielaviopsis paradoxa* and stored at 28 °C for seven days (Wijesinghe *et al*., 2010) [64]. Volatile organic compounds (VOCs) produced by *Trichoderma atroviride* IC-11 have demonstrated significant antifungal activity against *Botrytis cinerea*, the causative agent of gray mold in blueberries. *In vitro* studies revealed that these VOCs nearly completely inhibited *B. cinerea* growth. When applied as a mycofumigation treatment, the VOCs substantially reduced gray mold incidence in postharvest blueberries stored at both 20 °C and 4 °C, effectively suppressing rot development. The antifungal mechanism involves the inhibition of spore germination and mycelial growth, leading to vacuolation and deterioration of the fungal hyphae (Bello *et al*., 2020) [5]. Foliar and soil applications of *Trichoderma* species can effectively mitigate fungal diseases such as gray mold (*Botrytis cinerea*) and Fusarium wilt in grapevines. These fungi produce antimicrobial compounds like chitinases, glucanases, and peptaibols, which degrade pathogen cell walls, disrupt membranes, and inhibit essential enzymes, thereby reducing disease incidence and mold formation. In greenhouse experiments, inoculation of strawberry plants with *Funneliformis mosseae* or *Funneliformis geosporus*, as well as their combination, enhanced plant growth, increased yield, and improved water use efficiency under water stress conditions (Boyer *et al*., 2015) [7].

Beneficial Bacteria

Plant growth-promoting bacteria (PGPB) have emerged as promising, environmentally friendly bioregulators that enhance the sustainability of agricultural production systems.

Beneficial bacterial strains encompass a diverse array of genera, including *Acinetobacter*, *Azospirillum*, *Bacillus*, *Burkholderia*, *Arthrobacter*, *Beijerinckia*, *Pseudomonas*, *Azotobacter*, *Alcaligenes*, *Rhizobium*, *Enterobacter*, *Erwinia*, *Flavobacterium*, *Serratia*, *Acetobacter*, and *Paenibacillus* (Esitken *et al*., 2010) [22]. Plant growth-promoting bacteria (PGPB) interact with plant roots across three primary zones within the rhizosphere. The ectorhizosphere encompasses the soil region surrounding the root, where free-living bacteria thrive. Adjacent to this is the rhizoplane**,** which includes the root's surface and associated mucilage, serving as a habitat for bacteria that adhere directly to the root. Innermost is the endorhizosphere, comprising portions of the root's cortex and endodermis, where microbes occupy the spaces between cells (apoplastic space) (Sunitha *et al*., 2022) [61]. These distinct zones facilitate various beneficial interactions between PGPB and plant roots, contributing to enhanced plant growth and health.

Amongst the bacterial strains, the most promising benefits have been said to be obtained from Rhizobacteria. Plant growth-promoting rhizobacteria (PGPR) engage with plants through various interactions, including symbiotic relationships and colonization of niches from the rhizosphere to intracellular spaces. These associations, whether transient or lifelong, contribute to essential functions such as participation in biogeochemical cycles, nutrient supply, enhanced nutrient utilization, induction of resistance, increased stress tolerance, production of plant growth regulators, and control of morphogenesis (Hamid *et al*., 2021) [26]. PGPR are increasingly recognized as the "probiotics" of plants. They not only supply essential nutrients and enhance nutrient use efficiency but also induce disease resistance—partly through the production of volatile organic compounds like 2,3-butanediol. PGPR inoculants contribute to enhanced tolerance against various abiotic stresses, ultimately supporting improved plant health and productivity (Sunitha *et al*., 2022) [61]. Studies have shown that inoculating pear plants with specific plant growth-promoting rhizobacteria (PGPR) can enhance iron uptake and overall plant health. For instance, research involving pear saplings grafted onto BA-29 and OHF-333 rootstocks demonstrated that treatments with bacterial strains such as *Alcaligenes* 637Ca and *Staphylococcus* MFDCa1 significantly increased iron content in leaves and roots, as well as ferric chelate reductase (FC-R) activity, which is crucial for iron assimilation (İpek *et al*., 2017) [28]. Apart from this, PGPR also produce IAA along with cytokinins and gibberellins, which not only bolster plant defense and promote root elongation and biomass but also help modulate stomatal size and density. Besides, various genera—including *Rhizobium*, *Aeromonas*, *Azotobacter*, *Bacillus*, and *Pseudomonas*, are recognized IAA producers, with some strains also generating substantial gibberellins that further stimulate growth. Moreover, PGPR play a role in regulating ethylene levels, thereby ensuring proper plant development under a range of conditions (Hamid *et al*., 2021) [26].

It has been demonstrated in a study that inoculating strawberry plants with specific strains of plant growth-promoting bacteria, such as *Phyllobacterium* sp. PEPV15 and *Rhizobium* sp. PEPV16, can enhance the concentration of bioactive compounds in the fruits. Field experiments revealed that strawberries from plants treated with these bacterial strains exhibited significant increase in citric acid, vitamin C, and epicatechin levels compared to untreated controls. Further, inoculation with *Phyllobacterium* sp. PEPV15 led to a notable rise in anthocyanin content, particularly pelargonidin-3-O-rutinoside. These findings suggest that utilizing such bacterial biofertilizers is an effective agronomic practice to boost the nutritional quality and health benefits of strawberries (Flores-Félix *et al*., 2018). Research indicates that root inoculation with *Bacillus* M3, along with foliar applications of *Pseudomonas* BA-8 or *Bacillus* OSU-142, can enhance strawberry plant growth and yield. These treatments have been associated with increased concentrations of phosphorus (P), zinc (Zn), and other essential nutrients in plant tissues. Moreover, they have been found to contribute to improved soil nutrient availability, particularly phosphorus (P), potassium (K), and magnesium (Mg) (Esitken *et al*., 2010) [22].

Conclusion

Biostimulants represent an eco-friendly, innovative solution for enhancing stress tolerance, nutrient efficiency, and fruit quality in horticulture. Their integration into fruit production systems not only minimizes chemical input reliance but also supports plant resilience under adverse environmental conditions. As research advances, adopting tailored biostimulant strategies will be key to achieving sustainable and profitable fruit farming.

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References

1. Attia MS, Abdelaziz AM, Al-Askar AA, Arishi AA, Abdel Hakim AM, Hashem AH. Plant growth-promoting fungi as biocontrol tool against *Fusarium* wilt disease of tomato plant. Journal of Fungi. 2022;8:775-775.
2. Attia S, Mohamed GM, Ghobara M. Biostimulant activity of chitosan dissolved in different organic acids on tomato plant. Menoufia Journal of Plant Production. 2021;6:1-10. doi:10.21608/mjppf.2021.169081.
3. Behie SW, Bidochka MJ. Nutrient transfer in plant-fungi symbioses. Trends in Plant Science. 2014;19(11):734-740.
4. Begum N, Qin C, Ahanger MA, Raza S, Khan MI, Ashraf M, Ahmed N, Zhang L. Role of arbuscular mycorrhizal fungi in plant growth regulation: implications in abiotic stress tolerance. Frontiers in Plant Science. 2019;10:1068-1082. doi:10.3389/fpls.2019.01068.
5. Bello F, Montironi ID, Medina MB, Munitz MS, Ferreira FV, Williman C, Vázquez D, Cariddi LN, Musumeci MA. Mycofumigation of postharvest blueberries with volatile compounds from *Trichoderma atroviride* IC-11 as a promising tool to control rots caused by *Botrytis cinerea*. Food Microbiology. 2022;106:104040-104051. https://doi.org/10.1016/j.fm.2022.104040.
6. Boselli M, Bahouaoui MA, Lachhab N, Sanzani SM, Ferrara G, Ippolito A. Protein hydrolysates effects on grapevine (*Vitis vinifera* L. cv. Corvina) performance and water stress tolerance. Scientia Horticulturae. 2019;258:108784-108791.
7. Boyer LR, Brain P, Xu XM, Jeffries P. Inoculation of drought-stressed strawberry with a mixed inoculum of two arbuscular mycorrhizal fungi: effects on population dynamics of fungal species in roots and plant tolerance to water deficiency. Mycorrhiza. 2015;25(3):215-227.
8. Bryla DR, Vargas OL. Beneficial use of biostimulants in northern highbush blueberry. Acta Horticulturae. 2023;1357:43-50. https://doi.org/10.17660/ActaHortic.2023.1357.7.
9. Calvo P, Nelson L, Kloepper JW. Agricultural uses of plant biostimulants. Plant and Soil. 2014;383:3-41.
10. Canellas L, Olivares F, Aguiar N. Humic and fulvic acids as biostimulants in horticulture. Scientia Horticulturae. 2015;196:15-27. doi:10.1016/j.scienta.2015.09.013.
11. Colavita GM, Spera N, Blackhall V, Sepulveda G. Effect of seaweed extract on pear fruit quality and yield. Acta Horticulturae. 2011;909:601-607. doi:10.17660/ActaHortic.2011.909.72.
12. Colla G, Nardi S, Cardarelli M, Ertani A, Lucini L, Canaguier R, Rouphael Y. Protein hydrolysates as biostimulants in horticulture. Scientia Horticulturae. 2015;196:28-37. doi:10.1016/j.scienta.2015.08.037.
13. Dalpe Y, Monreal M. Arbuscular mycorrhiza inoculum to support sustainable cropping systems. Symposium Proceedings, Crop Management Network. 2004. https://doi.org/10.1094/CM-2004-0301-09-RV.
14. Del BD. Can biostimulants be used to mitigate the effect of anthropogenic climate change on agriculture? It is time to respond. Science of The Total Environment. 2021;751:141763-141775. https://doi.org/10.1016/j.scitotenv.2020.141763.
15. Demir S, Durak ED, Güneş H, Boyno G, Mulet JM, Rezaee Danesh Y, Porcel R. Biological control of three fungal diseases in strawberry (*Fragaria* × *ananassa*) with arbuscular mycorrhizal fungi. Agronomy. 2023;13(9):2439-2453.
16. Du Jardin P. Plant biostimulants: definition, concept, main categories and regulation. Scientia Horticulturae. 2015;196:3-14. doi:10.1016/j.scienta.2015.09.021.
17. El Kaissoumi H. Effect of *Trichoderma asperellum* on the development of strawberry plants and biocontrol of anthracnose disease caused by *Colletotrichum gloeosporioides*. In: Kacprzyk J, Ezziyyani M, Balas VE, editors. International Conference on Advanced Intelligent Systems for Sustainable Development (AI2SD 2022).

Lecture Notes in Networks and Systems, vol. 713. Cham: Springer; 2023. p. 745-755. https://doi.org/10.1007/978-3-031-35248-5_55.
18. El-Komy MH, Saleh AA, Eranthodi A, Molan YY. Characterization of novel *Trichoderma asperellum* isolates to select effective bio-control agents against tomato *Fusarium* wilt. Plant Pathology Journal. 2015;31(1):50-60.
19. El-Komy MH, Saleh AA, Ibrahim YE, Hamad Y. *Trichoderma asperellum* strains confer tomato protection and induce its defense-related genes against the *Fusarium* wilt pathogen. Tropical Plant Pathology. 2016;41:277-287.
20. El-Miniawy RM, Youssef S, Metwally A. Influence of foliar spraying of seaweed extract on growth, yield and quality of strawberry plants. Journal of Applied Sciences Research. 2014;10:88-94.
21. Ertani A, Francioso O, Ferrari E, Schiavon M, Nardi S. Spectroscopic-chemical fingerprint and biostimulant activity of a protein-based product in solid form. Molecules. 2018;23:1031-1040.
22. Esitken A, Yildiz HE, Ercisli S, Donmez MF, Turan M, Gunes A. Effects of plant growth-promoting bacteria (PGPB) on yield, growth and nutrient contents of organically grown strawberry. Scientia Horticulturae. 2010;124(1):62-66. https://doi.org/10.1016/j.scienta.2009.12.012.
23. Flores-Félix JD, Velázquez E, García-Fraile P, González-Andrés F, Silva LR, Rivas R. *Rhizobium* and *Phyllobacterium* bacterial inoculants increase bioactive compounds and quality of strawberries cultivated in field conditions. Food Research International. 2018;111:416-422.
24. Gunaydin S, Karaca H, Palou L, Fuente B, Pérez-Gago M. Effect of hydroxypropyl methylcellulose-beeswax composite edible coatings formulated with or without antifungal agents on physicochemical properties of plums during cold storage. Journal of Food Quality. 2017;2017:1-9. doi:10.1155/2017/8573549.
25. Gurav RG, Jadhav JP. A novel source of biofertilizer from feather biomass for banana cultivation. Environmental Science and Pollution Research International. 2013;20:4532-4539.
26. Hamid B, Zaman M, Farooq S, Fatima S, Sayyed RZ, Baba ZA, Sheikh TA, Reddy MS, El Enshasy H, Gafur A, Suriani NL. Bacterial plant biostimulants: a sustainable way towards improving growth, productivity, and health of crops. Sustainability. 2021;13(5):2856-2872. https://doi.org/10.3390/su13052856.
27. Hernandez OL, Garcia AC, Huelva R, Martínez-Balmori D, Guridi F, Aguiar NO, Olivares FL, Canellas LP. Humic substances from vermicompost enhance urban lettuce production. Agronomy for Sustainable Development. 2015;35:225-232.
28. İpek M, Aras S, Arıkan S, Eşitken A, Pırlak L, Dönmez MF, Turan M. Root plant growth-promoting rhizobacteria inoculations increase ferric chelate reductase (FC-R) activity and Fe nutrition in pear under calcareous soil conditions. Scientia Horticulturae. 2017;219:144-151. https://doi.org/10.1016/j.scienta.2017.02.043.
29. Kakar H, Khan A, Mouladad M, Nisar A, Shah SA. Effect of humic acid on fruit yield attributes, yield and leaf nutrient accumulation of apple trees under calcareous soil. Indian Journal of Science and Technology. 2018;11:1-8. doi:10.17485/ijst/2018/v11i15/119931.
30. Kamel HM. Impact of garlic oil, seaweed extract and imazalil on keeping quality of Valencia orange fruits during cold storage. Journal of Horticultural Science and Ornamental Plants. 2014;6:116-125.
31. Khan AS, Ahmad B, Jaskani MJ, Ahmad R, Malik AU. Foliar application of mixture of amino acids and seaweed (*Ascophyllum nodosum*) extract improves growth and physico-chemical properties of grapes. International Journal of Agriculture and Biology. 2012;14:383-388.
32. Kthiri Z, Jabeur MB, Harbaoui K, Karmous C, Chamekh Z, Chairi F, Serret MD, Araus JL, Hamada W. Comparative performances of beneficial microorganisms on the induction of durum wheat tolerance to *Fusarium* head blight. Microorganisms. 2021;9:2410-2423.
33. Kumar S, Teotia UVS, Sanghi A. Antioxidative property of cow milk caseinates hydrolyzed with different proteases. International Journal of Pharmaceutical Sciences. 2013;5:975-1491.
34. Lachhab N, Sanzani S, Adrian M, Chiltz A, Balacey S, Boselli M, Ippolito A, Poinssot B. Soybean and casein hydrolysates induce grapevine immune responses and resistance against *Plasmopara viticola*. Frontiers in Plant Science. 2014;5:716. https://doi.org/10.3389/fpls.2014.00716
35. Li X, Liao Q, Zeng S, Wang Y, Liu J. The use of *Trichoderma* species for the biocontrol of postharvest fungal decay in fruits and vegetables: Challenges and opportunities. Postharvest Biology and Technology. 2025;219:113236. https://doi.org/10.1016/j.postharvbio.2024.113236
36. Liu SY, Liao CK, Lo CT, Yang HH, Lin KC, Peng KC. Chrysophanol is involved in the biofertilization and biocontrol activities of *Trichoderma*. Physiological and Molecular Plant Pathology. 2016;96:1-7.
37. Liu Y, Gao L, Wang C, Chen FR, Jiang W, Yin C, Mao Z, Wang Y. Biochar combined with humic acid improves the soil environment and regulates microbial communities in apple replant soil. Ecotoxicology and Environmental Safety. 2024;283:116958. https://doi.org/10.1016/j.ecoenv.2024.116958
38. Lombardi N, Caira S, Troise AD, Scaloni A, Vitaglione P, Vinale F, Marra R, Salzano AM, Lorito M, Woo SL. *Trichoderma* applications on strawberry plants modulate the physiological processes positively affecting fruit production and quality. Frontiers in Microbiology. 2020;11:1364. https://doi.org/10.3389/fmicb.2020.01364
39. López-Bucio J, Pelagio-Flores R, Herrera-Estrella A. *Trichoderma* as biostimulant: exploiting the multilevel properties of a plant beneficial fungus. Scientia Horticulturae. 2015;196:109-123. https://doi.org/10.1016/j.scienta.2015.08.043
40. Machado LP, Matsumoto ST, Jamal CM, da Silva MB. Chemical analysis and toxicity of seaweed extracts with inhibitory activity against tropical fruit anthracnose fungi. Journal of the Science of Food and Agriculture. 2014;94(9):1739-1744.
41. Malerba M, Cerana R. Chitosan effects on plant systems. International Journal of Molecular Sciences. 2016;17(7):996. https://doi.org/10.3390/ijms17070996
42. Mancuso S, Briand X, Mugnai S, Azzarello E. Marine bioactive substances (IPA Extract) improve foliar ion uptake and water stress tolerance in potted *Vitis vinifera* plants. Advances in Horticultural Science. 2006;20(2):1000-1006.

43. McNear DH Jr. The rhizosphere—roots, soil and everything in between. Natural Sciences Education. 2013;4:1-5.
44. Morales-Pajan JP, Stall WM. *Carica papaya* response to foliar treatments with organic complexes of peptides and amino acids. Proceedings of the Florida State Horticultural Society. 2003;116:30-32.
45. Mousavi SM, Jafari A, Shirmardi M. The effect of seaweed foliar application on yield and quality of apple cv. 'Golden Delicious'. Scientia Horticulturae. 2024;323:112529. https://doi.org/10.1016/j.scienta.2023.112529
46. Neri D, Lodolini EM, Savini G, Sabbatini P, Bonanomi G, Zucconi F. Foliar application of humic acids on strawberry (cv. Onda). Acta Horticulturae. 2002;594:297-302. https://doi.org/10.17660/ActaHortic.2002.594.35
47. Nujthet Y, Kaewkrajay C, Kijjoa A, Dethoup T. Biocontrol efficacy of antagonists *Trichoderma* and *Bacillus* against post-harvest diseases in mango. European Journal of Plant Pathology. 2023;168:285-297. https://doi.org/10.1007/s10658-023-02757-1
48. Orozco-Mosqueda M, Flores A, Rojas-Sánchez B, Urtis-Flores CA, Morales-Cedeño LR, Valencia-Marin MF. Plant growth-promoting bacteria as bioinoculants: attributes and challenges for sustainable crop improvement. Agronomy. 2021;11:1167. https://doi.org/10.1002/jobm.202000370
49. Parvin N, Rahman A, Roy J, Rashid MH, Paul NC, Mahamud MA, Imran S, Sakil MA, Uddin FMJ, Molla ME, Khan MA, Kabir MH, Kader MA. Chitosan coating improves postharvest shelf-life of mango (*Mangifera indica* L.). Horticulturae. 2023;9(1):64. https://doi.org/10.3390/horticulturae9010064
50. Phelan M, Aherne A, FitzGerald J, O'Brien NM. Casein-derived bioactive peptides: biological effects, industrial uses, safety aspects and regulatory status. International Dairy Journal. 2009;19:643-654. https://doi.org/10.1016/j.idairyj.2009.06.001
51. Pichyangkura R, Chadchawan S. Biostimulant activity of chitosan in horticulture. Scientia Horticulturae. 2015;196:49-65. https://doi.org/10.1016/j.scienta.2015.09.031
52. Quartieri M, Lucchi A, Marangoni B, Tagliavini M, Cavani L. Effects of the rate of protein hydrolysis and spray concentration on growth of potted kiwifruit (*Actinidia deliciosa*) plants. Acta Horticulturae. 2002;594:341-347.
53. Rajan RK, Mali PC, Haldankar PM, Haldavanekar PC, Potphode PD. Effect of humic acid on growth of mango (*Mangifera indica* L.) nursery grafts cv. Alphonso. Journal of Pharmacognosy and Phytochemistry. 2018;7(6):2778-2780.
54. Rana VS, Sharma V, Sharma S, Rana N, Kumar V, Sharma U, Almutairi KF, Avila-Quezada GD, Abd_Allah EF, Gudeta K. Seaweed extract as a biostimulant agent to enhance the fruit growth, yield, and quality of kiwifruit. Horticulturae. 2023;9(4):432. https://doi.org/10.3390/horticulturae9040432
55. Rees HJ, Drakulic J, Cromey MG, Bailey AM, Foster GD. Endophytic *Trichoderma* spp. can protect strawberry and privet plants from infection by the fungus *Armillaria mellea*. PLoS One. 2022;17(8):e0271622.
56. Rose MT, Patti AF, Little KR, Brown AL. A meta-analysis and review of plant-growth response to humic substances. [Incomplete citation - page numbers or journal missing; please provide for completion.]
57. Rouphael Y, Franken P, Schneider C, Schwarz D, Giovannetti M, Agnolucci M, *et al*. Arbuscular mycorrhizal fungi act as biostimulants in horticultural crops. Scientia Horticulturae. 2015;196:91-108. https://doi.org/10.1016/j.scienta.2015.09.002
58. Sajid M, Basit A, Ullah Z. Chitosan-based foliar application modulated the yield and biochemical attributes of peach (*Prunus persica* L.) cv. Early Grand. Bulletin of the National Research Centre. 2020;44:150. https://doi.org/10.1186/s42269-020-00405-w
59. Singh RK, Ruiz-May E, Rajput VD, Minkina T, Gómez-Peraza RL, Verma KK, Shekhawat MS, Pinto C, Falco V, Quiroz-Figueroa FR. Viewpoint of chitosan application in grapevine for abiotic stress/disease management towards more resilient viticulture practices. Agriculture. 2022;12(9):1369.
60. Spinelli F, Fiori G, Noferini M, Sprocatti M, Costa G. Perspectives on the use of a seaweed extract to moderate the negative effects of alternate bearing in apple trees. Journal of Horticultural Science and Biotechnology. 2009;84(6):131-137.
61. Sunitha C, Madhavi M, Dean A, Sandhyarani M, Jasmitha M, Srinivasulu B, Kumar PP. Role of biostimulants in fruit crops: a review. 2022;11(8):2041-2048. [Journal name missing - please specify.]
62. Teklić T, Parađiković N, Špoljarević M, Zeljković S, Lončarić Z. Abiotic stress, plant metabolites, biostimulants and functional food. Annals of Applied Biology. 2021;178:169-191.
63. Wang H, Zhang R, Mao Y, Jiang W, Chen X, Shen X, Yin C, Mao Z. Effects of *Trichoderma asperellum* 6S-2 on apple tree growth and replanted soil microbial environment. Journal of Fungi. 2022;8(1):63. https://doi.org/10.3390/jof8010063
64. Wijesinghe CJ, Wilson Wijeratnam RS, Samarasekara JKRR, Wijesundera RLC. Biological control of *Thielaviopsis paradoxa* on pineapple by an isolate of *Trichoderma asperellum*. Biological Control. 2010;53(3):285-290.
65. Yakhin OI, Lubyanov AA, Yakhin IA, Brown PH. Biostimulants in plant science: a global perspective. Frontiers in Plant Science. 2017;7:2049. https://doi.org/10.3389/fpls.2016.02049
66. Yang C, Lu JH, Xu MT, Shi XC, Song ZW, Chen TM, Herrera-Balandrano DD, Zhang YJ, Laborda P, Shahriar M. Evaluation of chitosan coatings enriched with turmeric and green tea extracts on postharvest preservation of strawberries. LWT. 2022;163:113551.
67. Yang S, Wang H, Wang G, Wang J, Gu A, Xue X, Chen R. Effects of seaweed-extract-based organic fertilizers on the levels of mineral elements, sugar-acid components and hormones in *Malus domestica* cv. Fuji. Agronomy. 2023;13(4):969. https://doi.org/10.3390/agronomy13040969
68. Yassin MT, Mostafa AA, Al-Askar AA, Sayed SRM, Rady AM. Antagonistic activity of *Trichoderma harzianum* and *Trichoderma viride* strains against some *Fusarium* pathogens causing stalk rot disease of maize *in vitro*. Journal of King Saud University - Science. 2021;33:101363.
69. Zulfiqar F, Casadesús A, Brockman H, Munné-Bosch S. An overview of plant-based natural biostimulants for sustainable horticulture with a particular focus on *Moringa* leaf extracts. Plant Science. 2020;295:110194