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A complete systematic review on biostimulant in fruit crops and their industrial applications

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Abstract

Fruit crops are vital to global agriculture, offering significant nutritional, health, and economic benefits. However, achieving high quality produce and scaling productivity are hindered by biotic and abiotic stresses, excessive reliance on agrochemicals, and shifting environmental conditions. Plant biostimulants have consequently gained considerable attention as a sustainable strategy to enhance fruit crop growth, yield, quality, and stress resilience. This review provides a comprehensive analysis of the functions of both microbial and non-microbial biostimulants in fruit production. It further explores their classification and modes of action, detailing how they influence on nutrient use efficiency, root architecture, hormonal balance, metabolic processes, and defense mechanisms. Finally, the review emphasizes the critical need to optimize application rates and timing, and to develop targeted, crop-specific strategies for effective implementation.

1. Introduction

Fruit crops play an important role in modern agriculture, as people are now aware of the nutritional and nutraceutical benefits of fruits, which has led to demand surged. According to the recent APEDA data, India ranks second in fruit production, with Maharashtra being the largest producer within the country. To meet this demand, the use of synthetic fertilizers and pesticides has also increased, but as people are now more conscious about human health and envir onmental sustainability, they prefer organic or eco-friendly products. The European Biostimulant Industry Council (EBIC) defines plant biostimulants as plant biostimulants contain substance(s) and/or microorganisms whose function, when applied to plants or the rhizosphere, is to stimulate natural processes to improve crop quality, abiotic stress tolerance, nutrient efficiency, and nutrient uptake. The quality of fruit is primarily assessed through a combination of physical properties, chemical composition, and nutritional value, with consumer preference serving as the ultimate determinant of acceptance. Consumers mainly prefer the products that are visually appealing with good shape, colour, size, and free from any damage, but these can vary with fruits, for example, while selecting grapes for wine purposes, the important factor here is phenolic content, which is directly related to the wine quality. The quality of the fruit can also depend on the field practices followed and the environmental conditions (Dorais *et al.*, 2008; Di Vittori *et al.*, 2018). There are various experimental results that show the positive effect of biostimulants on fruit quality. Gonçalves *et al.* (2020) reported that the application of seaweed (*Ascophyllum nodosum*) reduced the craking index and increased fruit width, weight, diameter, pH, and wax.

The quality and yield characters can be mainly affected by biotic and abiotic factors. Biotic factors include bacteria, fungi, and viruses, which will cause infectious diseases and pests that feed on the crop, which is also a reason for the spread of these diseases. This will affect the crop health and decrease the yield. To control these, mainly pesticides and other chemicals are used traditionally, which will

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increase the health risk and also degrade the soil health. The abiotic factors include temperature fluctuation (low and high temperatures), drought, and soil composition (extreme salinity, acidity, and sodicity). To control these in a sustainable manner, the use of plant biostimulants can be utilized as they have various characteristics that have the ability to withstand these situations, like seaweed extract, which can be used to control stress and various other characteristics (Sunitha *et al.,* 2022). Most reviews on biostimulants cover broad agricultural crops (cereals, vegetables, field crops) without focusing specifically on fruit crops, which have distinct physiological, phenological, and market-quality requirements. This review is novel in that it consolidates evidence specifically from fruit crop species (mango, citrus, grapes, banana, apple, strawberry, *etc.*), categorizes biostimulants by type and mechanism, and addresses fruit-quality parameters such as TSS, acidity, shelf-life, and nutraceutical content parameters rarely emphasized in generalized reviews.

2. Classification of biostimulant

The concept of external application of natural substances like seaweed, manures, and compost has been used from early times for enhancing crop performance (Khoulati *et al.,* 2025). Biostimulants emerged as a formal scientific category through an evolutionary process. The field originated with the late-19th-century discovery of rhizobium, pioneering the use of microbial inoculants (Bashan *et al.,* 2014). A century of subsequent research, including work on non-microbial agents like seaweed extracts, proved that growth could be enhanced through non-nutritional physiological stimulation (Craigie *et al.,* 2011). This cumulative knowledge was later codified under the inclusive biostimulant concept, which encompasses any substance or microorganism applied to plants for such physiological benefits (Yakhin *et al.,* 2017). Biostimulants can be live bacteria or complex chemical mixtures. The primary classification is based on the active component, resulting in two basic groups (Rouphael *et al*., 2020; Calvo *et al.,* 2014). The biostimulants are: i. microbial biostimulant and ii. non-microbial biostimulant.

2.1 Microbial biostimulant

The use of beneficial microbes can affect the biological structure of the soil and support the growth of additional beneficial bacteria, which further boost soil fertility and lead to increased crop output, as well as assist in the restoration of the soil's natural microflora (Rouphael *et al.,* 2020; Tarafdar *et al.,* 2022). The inconsistent performance of microbial biostimulants under field conditions can be attributed to several interacting factors. Introduced PGPR (plant growth promoting rhizobacteria) and AMF (arbuscular mycorrhizal fungi) strains often struggle to establish themselves due to competition from native soil microbial communities that are already well-adapted to local conditions. Beyond biological competition, environmental stresses such as high temperatures, UV exposure, drought, and unfavourable soil pH can quickly reduce the viability of applied microorganisms before meaningful plant colonization occurs. Storage and handling also matter, as live microbial products may lose a significant proportion of viable cells, if temperature conditions are not maintained properly during transport or storage. Soil texture further influences outcome, since colonization efficiency of AMF and PGPR differs between sandy, loamy, and clay soils. Additionally, the choice of application method, whether seed coating, soil drenching, or foliar spray, determines which ecological zone the microorganism reaches, and a mismatch between the method and the organism's target site of action can render the application largely ineffective.

Among microbial biostimulants, *Rhizobium, Azotobacter,* and *Azospirillum* constitute the most widely adopted and researched microorganisms; all are selected for their non-pathogenic and non-toxigenic properties (Barros *et al*., 2020). The PGPR (plant growth promoting rhizobacteria), which include *Alcaligenes, Azospirillum, Arthrobacter, Azotobacter, Bacillus, Enterobacter, Burkholderia, Klebsiella, Pseudomonas, Rhizobium,* and *Serratia* are now widely used as biocontrol cum biofertilizers (Kloepper *et al.,* 2004). These have been widely utilized for sustainable cultivation as they have the ability to promote growth and development, and also to level up the yield.

2.1.1 Arbuscular mycorrhizal fungi (AMF)

Arbuscular mycorrhizal fungi are known to improve soil characteristics by improving soil structure, which in turn will benefit plant growth. The excretion of glomalin acts as glue in soil and forms large aggregates, which will increase soil resistance to water and wind erosion (Syamsiyah *et al.,* 2017; Bowles *et al.,* 2016). Arbuscular mycorrhizal fungi are also found to increase the water holding capacity and subside the nutrient leaching (Bender *et al.,* 2015). Mycorrhizal symbiosis starts when the plant is grown in poor soil with low phosphorus. In such conditions, the plant roots will release a chemical known as strigolactones into the soil. These signals will stimulate AMF spores to germinate and grow. The response is by changing their metabolism and producing branching hyphae as they move towards the roots. The fungi will release a signaling molecule known as mycorrhizal factors (Myc factor), which activates symbiosis-related genes in plant roots and prepares them for fungal entry. Once the fungus reaches the root, it will enter through the outer cell layer and move inside the root tissues. There, it forms a tiny, tree like structure called arbuscules inside the root cells. These structures act as an exchange point between the plant and the fungus. Arbuscules will remain active only for a few days and then break down naturally, leaving the plant cells healthy and unchanged. The fungus also makes storage structures and new spores, which help it survive and spread to new plants. The improved absorption of mineral elements, including calcium, phosphorus, copper, zinc, sulfur, and iron, as well as the enhanced resilience to different kinds of biotic and abiotic stress, are the two most important positive effects of arbuscular mycorrhizal fungi (Siddiky *et al.,* 2012). In his experiment, Yu *et al.* (2021) discovered that the biological nitrogen fixation (BNF) process in mangrove ecosystems was driven by α-diversity of AMF and diazotrophic communities, N-related enzymes, and sediment nutrition elements. AMF boosted nutrient uptake, notably phosphorus and other less mobile elements, largely by increasing the absorptive surface of hyphal exploration in the rhizosphere. It also performed as soil reclamation and biocontrol agents for contaminated or polluted soil (Tekaya *et al*., 2021). Gazioglu *et al.* (2022) on grapevines reported that salt induced damage was significantly reduced when plants were treated with AMF, and it was also observed that AMF helped the plants to absorb important nutrients like phosphorus and potassium. Some positive effects of AMF on fruit crops are given in Table 1.

Table 1: Influence of Arbuscular mycorrhizal fungi (AMF) inoculation on growth, yield and nutrient acquisition in selected fruit crops

Fruit crops	Benefits of AMF application	References
Peach *Prunus persica* (L.) Batsch	Increase the growth, absorption of nitrogen, phosphorus, and potassium	Da Silva Nunes *et al.,* 2025
Citrus (*Citrus* spp.)	Increase biomass, stem diameter, and plant height	Menge *et al.*, 1978
Grapevine *Vitis vinifera* L.	Improved plant growth and nutrient absorption compared to non-mycorrhizal plants	Schubert *et al.*, 1988
Apple *Malus domestica* (Suckow) Borkh.	Improved seedling growth, leaf area, and biomass accumulation	Plenchette *et al.,* 1983
Strawberry (*Fragaria* spp.)	Increased leaf number, leaf area, and shoot dry weight	Trouvelot *et al.*, 1986
Banana (*Musa* spp.)	Resulted in taller plants, greener leaves, and higher bunch weight	Declerck *et al.*, 1995

Efficacy varies considerably across fruit crops due to differences in root architecture, growth duration, climatic adaptation, and physiological responses. For example, mycorrhizal fungi show strong benefits in drought stressed citrus and grapes but may be less effective in crops with fine fibrous root systems under well-watered conditions. Seaweed extracts tend to show more consistent results in strawberries and grapes, while amino acid-based biostimulants show variable responses depending on growth stage and crop species. Tropical fruit crops like mango and banana show responses to humic acid and PGPR but the data density is lower compared to temperate fruits.

Table 2: Effects of seaweed extract application on growth, yield and quality parameters of tropical and subtropical fruit crops

Fruit crops	Effects on growth, yield, and quality	References
Mango *Mangifera indica* L.	Promotes vegetative growth, enhances nitrogen, phosphorus, and potassium uptake, improves fruit set, yield, and fruit quality, increases IAA (indole-3-acetic acid), carotenoid, and photo-synthetic pigment contents, enhances drought tolerance, and extends shelf-life	Mohamed and Sehrawy, 2013; Abdel-Sattar *et al.,* 2024
Guava (*Psidium guajava* L.)	Improved flower retention, fruit set percentage, and fruit weight	Saishree *et al*., 2024
Papaya *Carica papaya* L	Improved fruit firmness and sensory parameters like colour, texture, flavour, and appearance	Patel *et al*., 2021
Lemon *Citrus limon* (L.) Osbeck	When combined with zinc enhanced the growth, biomass accumulation, chlorophyll content, and nutrient status	Aswad and Abbasi, 2025
Mandarin orange *Citrus reticulate* Blanco	Increased fruit weight, soluble solid content, reducing sugar and yield	Khan *et al*., 2022
Sweet orange *Citrus sinensis* (L.) Osbeck	Increase fruit set, yield, quality and decrease fruit drop	Hikal *et al*., 2015
Pomegranate *Punica granatum* L.	Improved fruit size, weight, TSS % and yield	Hussein *et al*., 2021
Grapes *Vitis vinifera* L.	Increased chlorophyll content, berry size rachis length, berry size, soluble solid concentrations, reducing sugar and total sugar, reduced berry drop	Khan *et al*., 2012
Date palm *Phoenix dactylifera* L.	Promote growth, TSS (total soluble solids), sugars, fruit size, photosystem II efficiency, and vascular tissues	Anli *et al*., 2020
Fig *Ficus carica* L.	Promote growth, fruit quality, and yield	Hameedawi and Malikshah, 2017
Litchi *Litchi chinensis* Sonn.	Promote yield and fruit quality	Nayak *et al*., 2024
Kiwifruit *Actinidia* spp.	Increase soluble solids content and sugars, decrease acidity and harvest earlier	Rana *et al*., 2023

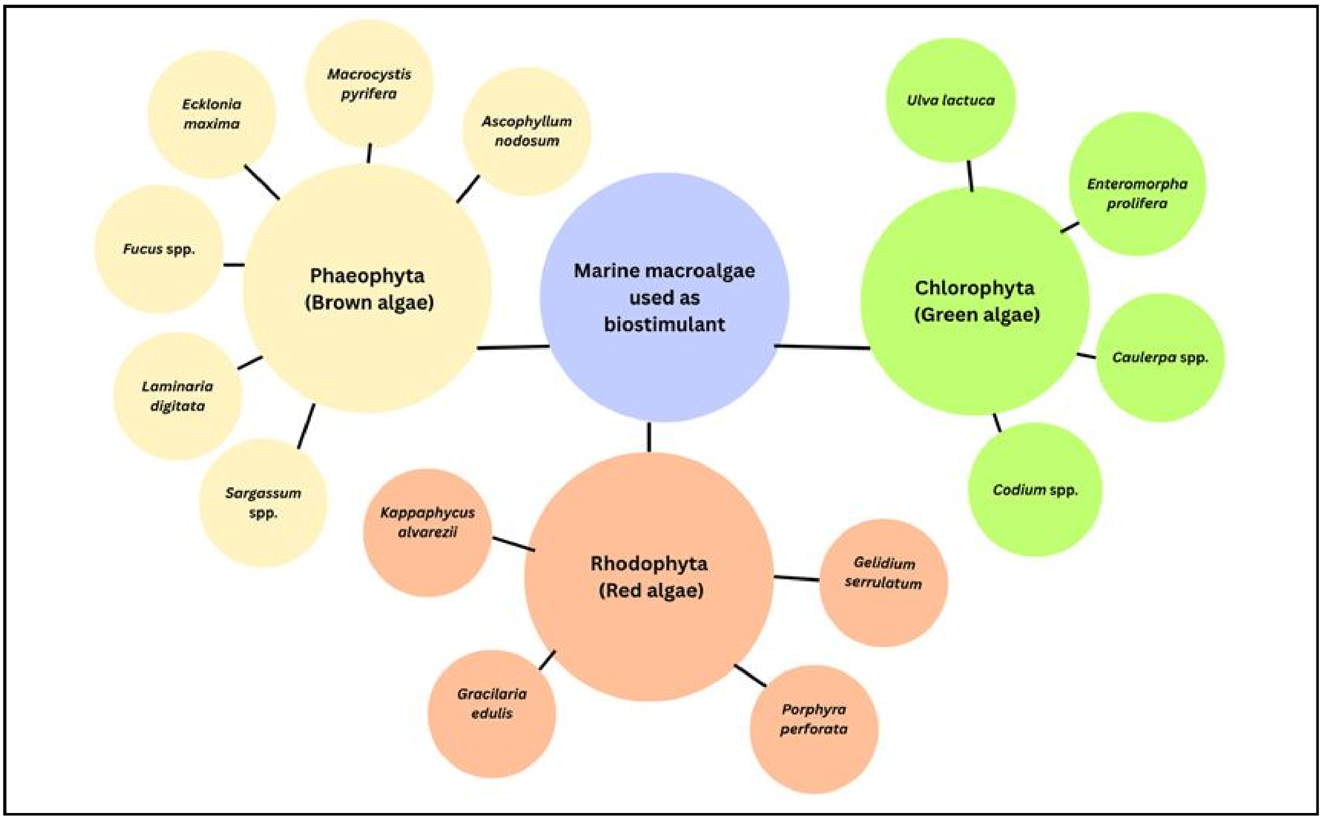

Figure 1: Schematic representation of major macroalgae used as biostimulant.

2.2 Non-microbial biostimulant

2.2.1 Seaweed extract

Marine algae are frequently used to improve soil fertility, manage stress, and promote plant development; their effects have lately been studied (Rouphael *et al.,* 2020). Some of the marine macro algae used as biostimulants are given in Figure 1. Seaweed extract contains various bioactive compounds such as terpenoids, polyphenols, and sulphated polysaccharides (Sekar *et al.,* 2025). The extraction can be done using various methods, and each method has their own benefits. The methods are supercritical fluid extraction, solvent extraction, microwave-assisted extraction, aqueous extraction, enzyme-assisted extraction, acid hydrolysis, and hydrothermal liquefaction. The use of seaweed in fruit crops and its effect is given in the Table 2.

2.2.2 Humic substance

Humic substance are classified into three main fractions as humic acid, fulvic acid, and humans (Stevenson *et al*., 1994; Berbara and García, 2014). Humic acid and fulvic acid are important non-microbial biositmulants used in horticulture for various benefits like plant growth, stress tolerance, and nutrient use efficiency (Canellas *et al*., 2014; Bulgari *et al*., 2019). These originate from the decomposition and humification of plant and animal residues. The important effects of humic acids are the ability to stimulate root system development. The application of humic acid is found to promote the lateral root initiation, root elongation, and root hair formation, which will result in an increase in absorptive surface area. This action has been linked to auxin-like activity and stimulation of H^+-ATPase in the plasma membrane, which results in increased cell wall loosening and rhizosphere acidification in line with the acid growth process (Canellas *et al*., 2014; Zandonadi *et al*., 2007; Nardi *et al*., 2021). Some of the effect of humic acid in fruit crops is given in Table 3. In soil, humic acids play a multifunctional role which includes regulation of nutrient availability, improvement of soil structure, and mediation of carbon and oxygen exchange processes. This strong chelating capacity allows them to bind metal ions, thereby affecting the mobility and bioavailability of both essential nutrients and potentially toxic elements (Piccolo and Spiteller, 2003; Schiavon *et al*., 2010). Due to its multifunctional properties, it is widely used in the horticulture field. However, the responses may vary depending on humic acid source, concentration, crop species, and environmental factors (Feller *et al*., 2010; Lamar *et al*., 2013).

2.2.3. Protein hydrolysates

Protein hydrolysates are a mixture of amino acids, peptides, and organic compounds that is derived from the enzymatic or chemical hydrolysis of protein rich sources from plants, animals or algae (Paskoviæ *et al*., 2024). They are commonly used in the horticulture field to reduce the reliance on synthetic fertilizers. The effects are root development, which stimulates the length, surface area, and biomass via auxin-like activity, which is often due to tryptophan content (Paskoviæ *et al*., 2024; Colla *et al*., 2015). Animal-based protein hydrolysates increased root length by up to 94% and biomass by 152% in tea and chickpea (Raguraj *et al*., 2023). Shoot growth is also observed to improve by the application of Protein hydrolysates have shown an enhancement in shoot biomass, plant height, leaf area, and yield through gibberellins and cytokinin-like effects (Paskoviæ *et al*., 2024). Nutrient metabolism has also been seen to be improved, N and C assimilation by increasing activities of glutamine synthetase (GS), glutamate synthase (GOGAT), and TCA (tricarboxylic acid cycle) cycle enzymes, and enzyme nitrogen use efficiency (Paskoviæ *et al*., 2024; Ertani *et al*., 2009). They also showed to promote the vegetative growth and macro and micronutrient uptake, which will increase the crop productivity (Halpern *et al*., 2015). The Table 4 shows the effect of protein hydrolysate on the growth, yield, and quality of fruit crops.

Table 3: Impact of humic acid application on vegetative growth, fruit yield and quality attributes of various fruit crops

Fruit crops	Humic acid application	Effect on growth/yield/fruit quality	References
Plum *Prunus domestica* L.	Soil, foliar and combined	Combined soil and foliar humic acid increased vegetative growth (height, shoots), leaf nutrient content (N, P, K, Fe, Mn, and Zn), highest yield and fruit quality, 10 day irrigation with humic acid most efficient	Shall *et al*., 2010
Pear *Pyrus* spp.	Foliar spray at 4-5% humic acid	Increased shoot length, leaf area, fruit weight and size, TSS(total soluble solids), sugars, improved fruit set and yield, enhanced leaf macro and micronutrients	Mosa *et al*., 2022
Mango *Mangifera indica* L.	Foliar humic acid at 0.15-0.45% (with/without boron)	Improved fruit quality, productivity, flowering and tree growth, humic acid and micronutrients are frequently superior to humic acid alone	Hoseiny *et al*., 2020
Mango *Mangifera indica* L.	Foliar humic acid 1.5% (with potassium silicate)	Improved fruit number, yield, fruit length and weight	Aal *et al*., 2024
Mango (*Mangifera indica* L.)	Foliar humic acid at 1-2%	Increased fruit yield and quality traits	Patel *et al*., 2020
Apple *Malus domestica* (Suckow) Borkh.	Foliar humic acid and micronutrient mixtures	Increased leaf area, shoot growth, fruit number, yield per tree, and fruit quality (size, weight, soluble solids content)	Boray *et al*., 2015

Table 4: Response of fruit crops to protein hydrolysate application

Fruit crops	Type/source of protein hydrolysate	Application method	Effects on growth, yield and quality	References
Papaya *Carica papaya* L.	Animal-derived protein hydrolysates (Siapton)	Foliar	Increased marketable yield (~22%), improved fruit number due to enhanced fruit set	Morales and Stall, 2003
Grapevine *Vitis vinifera* L.	Soybean and casein-derived protein hydrolysates	Foliar	Up-regulation of defense-related genes (stilbene synthase), and enhanced resistance to *Plasmopara viticola*	Lachhab *et al*., 2014
Grapevine *Vitis vinifera* L.	Plant-derived protein hydrolysates	Foliar	Improved drought tolerance, increased soluble solids, total phenols and anthocyanins in berries	Boselli *et al*., 2015
Persimmon *Diospyros kaki* L.	Animal-derived protein hydrolysates enriched with Ca	Root	Reduced chloride uptake, decreased leaf necrosis, and improved salinity tolerance	Visconti *et al*., 2015

3. Mode of action

Plant growth is mainly governed by fundamental cellular processes, which include cell division, expansion, and cell differentiation (Longnecker *et al.,* 1994; Wang and Ruan, 2013). These are the processes that determine the organ size and structure, which directly influence the yield (Wang and Ruan, 2013). The biostimulant like protein hydrolysates influence the expression of genes involved in cell wall synthesis and remodeling, resulting in improved cell flexibility and enhanced cell expansion (Colla *et al.,* 2015; Zuluaga *et al.,* 2023). Biostimulant's effect is attributed to modulating endogenous physiological and molecular processes rather than directly supplying nutrients. Their mode of action primarily includes metabolic priming, hormonal regulation, and signal transduction. They help in the modulation of phytochrome homeostasis. The microbial biostimulant will help to synthesize auxin, cytokinin, and gibberellin, which will regulate the developmental process, including cell division, elongation, and differentiation. This will result in improvement in root system architecture, enhance lateral root formation, and increase shoot growth. Such structural and physiological improvements strengthen plant capacity for water and nutrient uptake and indirectly enhance tolerance to both abiotic and biotic stresses (Spaepen *et al*., 2014; Vacheron *et al*., 2013; Rouphael *et al.,* 2020).

Biostimulants also help in metabolic activities like nitrogen and carbon assimilation. They enhance the enzymes that are involved in nitrogen uptake and assimilation, such as nitrate reductase and glutamine synthetase, and improve carbon metabolism by stimulating photosynthetic efficiency and respiratory processes. These effects will improve the nutrient use efficiency, higher biomass accumulation, and increased yield (Colla *et al*., 2015). Under abiotic stress conditions, including drought, salinity, and temperature extremes, biostimulants induce physiological adjustments that will maintain cellular homeostasis. They promote the accumulation of compatible osmolytes such as proline and glycine betaine, which contribute to osmotic adjustment, membrane stabilization, and maintenance of cell turgor. In addition, biostimulants enhance the antioxidant defense system by upregulating reactive oxygen species (ROS) scavenging enzymes, which include superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), along with the stress responsive genes encoding protective proteins such as heat shock proteins (HSPs) and late embryogenesis abundant (LEA) proteins. Together, these mechanisms will mitigate the oxidative damage and preserve cellular integrity under stress conditions (Khalid *et al*., 2024).

In response to biotic stress, biostimulants activate the plant immune response through induced resistance mechanisms. Beneficial microorganisms such as PGPR and *Trichoderma* spp. Trigger jasmonic acid (JA) and ethylene dependent induced systemic resistance (ISR), resulting in a primed defense state that enables faster and stonger activation of plant defense upon pathogen attack. This response has been observed by various experiments, such as in cucumber (Shoresh *et al*., 2005). In contrast, certain non-microbial biostimulants such as seaweed extract will stimulate salicylic acid mediated systemic acquired resistance (SAR), which is effective against biotrophic pathogens (Khompatara *et al*., 2019). Beyond host mediated defense activation, microbial biostimulants exert direct antagonistic effects against plant pathogens by competing with harmful microbes for space and nutrients. Some beneficial microbes also produce antibiotics and siderophores, which inhibit or starve the pathogen, as well as enzymes that break down pathogen cell walls (Tariq *et al*., 2020; Carmona-Hernandez *et al*., 2019).

4. Role of biostimulant in growth

Plant biostimulants have been used as a sustainable replacement for synthetic fertilizers and is observed to improve the vegetative growth of fruit crops. When combined with conventional fertilization techniques, biostimulants improve nutrient utilization efficiency and fortify plant's resilience, promoting both environmental sustainability and productivity (Du Jardin, 2015; Melini *et al.,* 2023). Some of the most notable research on the effect of various biostimulators on fruit crops, particularly with regard to growth, production, and fruit quality, is given in the Table 5. Several studies reported neutral or inconsistent results, particularly when biostimulants are applied under non stress conditions where the crop does not have a limiting factor to overcome. Microbial inoculants (PGPR and AMF) sometimes show no significant response when native soil microbial populations are already robust, or when soil nutrient levels are already optimal. Humic acids at high doses occasionally suppress germination or root growth. Seaweed extract responses are dose and timing dependent late season applications sometimes show no fruit quality improvement. These inconsistencies highlight the importance of calibrating application rates, timing, and crop-specific protocols. Fathy *et al.* (2010) in their study observed that the application of humic acid in apricot promotes the growth characteristics, which include shoot length, and also helps in fruit yield and quality. Similarly, improvement in growth characters like increase in plant height, leaf area, plant spread, girth at collar, root length, number of secondary and tertiary roots was recorded in the mango crop (Rajan *et al*., 2018). The shoot length, leaf area, and chlorophyll content were also found to improve when a combination of chitosan, salicylic acid, and fulvic acid was used in grapevines (El-Kenawy *et al*., 2017).

Table 5: Effects of biostimulant treatments on growth characteristics in fruit crops

Fruit crops	Biostimulant	Mode of application	Vegetative growth improvement	References
Apricot *Prunus armeniaca* L.	Humic substances (Actosol®)	Foliar and soil	Promote shoot length and total chlorophyll content	Fathy *et al*., 2010
Pineapple *Ananas comosus* L.	Humic acid + vermi-compost + microbes	Soil	Promote growth and acclim-atization of plantlets	Baldotto *et al.,* 2010
Strawberry *Fragaria* spp.	Humic acids	Foliar and fertigation	Enhance nutrient use efficiency and vegetative vigor	Tehranifar *et al*., 2012
Passion fruit *Passiflora* spp.	Humic acids	Foliar	Promote root dry weight, and improved seedling quality	Cavalcante *et al.,* 2013
Acid lime *Citrus aurantifolia* Swingle	Humic acid	Soil	Promote shoot fresh and dry weight, and root dry weight	Jahromi and Hassanzadeh, 2016
Mango *Mangifera indica* L.	Humic acids	Drenching	Promote plant height, leaf area, stem girth, and root growth	Rajan *et al.,* 2018
Strawberry *Fragaria* spp.	Nitrogen + humic acid	Soil and foliar	Promote leaf area, chlorophyll a, and carotenoids	Rostami *et al*., 2022
Strawberry *Fragaria* spp.	Potassium phosphite	Soil	Promote root and shoot growth	Glinicki *et al.,* 2010
Sour orange *Citrus* spp.	Seaweed extract + CPPU (Forchlorfenuron)	Foliar	Promote seedling height, leaf number, and stem diameter	Ali and Al-Araji, 2020
Mango *Mangifera indica* L.	Seaweed extract	Foliar	Promote leaf N, K, Fe, and Zn content	Al-Marsoumi and Al-Hadethi, 2020
Date palm *Phoenix dactylifera* L.	Coconut milk + case in hydrolysate	Foliar	Promote chlorophyll, carbo-hydrates, and proteins	Hosny *et al*., 2016

Grapevine *Vitis vinifera* L.	Chitosan + SA (salicylic acid) + fulvic acid	Foliar	Promote shoot length, leaf area, and chlorophyll	El-Kenawy, 2017
Grapevine *Vitis vinifera* L.	Arbuscular mycorrhizal fungi	Soil	Promote chlorophyll, carote-noids, and phenols	Krishna *et al*., 2005
Citrus *Citrus* spp.	Arbuscular mycorrhizal fungi	Soil	Promote plant height, biomass and photosynthesis	Wu *et al*., 2010
Loquat *Eriobotrya japonica* (Thunb.) Lindl.	Arbuscular mycorrhizal fungi (*Funneliformis mosseae*)	Soil	Promote dry biomass and leaf water potential	Zhang *et al*., 2015
Strawberry *Fragaria* spp.	*Bacillus licheniformis*	Root dip and foliar	Promote vegetative growth	Kumari *et al*., 2018

5. Role of biostimulant in fruit yield, quality, and postharvest

In crop production, yield is a crucial factor in addition to quality and postharvest life for successful marketing in both local and distant markets. From various studies, positive effects are observed on the fruit crop on yield and quality characters, which include an increase in fruit set, fruit yield per tree, quality characters, and shelf-life have also been seen to be influenced by the application of different biostimulants. The given Table 6 contains the effect of different biostimulants on yield, quality, and post-harvest in fruit crops.

Table 6: Effects of biostimulant treatments on fruit yield, quality attributes and postharvest characteristics in fruit crops

S. No.	Fruit crops	Biostimulant	Mode of application	Yield improvement	References
1	Apricot *Prunus armeniaca* L.	Humic substances (Actosol®)	Foliar and soil	Promote fruit yield	Fathy *et al*., 2010
2	Strawberry *Fragaria* spp.	Humic acid	Foliar	Promote yield (33%)	Farahi *et al*., 2013
3	Strawberry *Fragaria* spp.	HA + seaweed extract	Soil and foliar	Promote fruit yield	Alkharpotly *et al*., 2017
4	Strawberry *Fragaria* spp.	Nitrogen + humic acid	Soil and foliar	Promote fruit yield	Rostami *et al*., 2022
5	Strawberry *Fragaria* spp.	Potassium phosphite	Root application	Promote plant productivity	Glinicki *et al*., 2010
6	Mango *Mangifera indica* L.	Seaweed extract	Foliar	Promote fruit yield, larger fruits	Mohamed and El-Sehrawy, 2013
7	Banana *Musa* spp.	Seaweed (*Ascophyllum nodosum*)	Foliar	Promote bunch weight and yield	El-Kholy, 2017
8	Strawberry *Fragaria* spp.	Seaweed extract (Alga 600)	Fertigation	Promote yielding units per plant	Al-Shatri *et al*., 2020
9	Grapes *Vitis vinifera* L.	Seaweed extract	Foliar	Promote yield and berry attributes	El-Sese *et al*., 2020
10	Banana *Musa* spp.	Protein hydrolysate	Soil and foliar	Promote fruit bioche-mical yield traits	Gurav and Jadhav, 2013
11	Pecan nut *Carya illinoinensis* (Wangenh.) K.Koch	Protein hydrolysate (Supramino)	Foliar	Promote nut and kernel yield	Iqbal *et al*., 2013
12	Grapevine *Vitis vinifera* L.	Protein hydrolysates	Foliar	Promote yield per vine	Boselli *et al*., 2019
13	Mango *Mangifera indica* L.	Nano-chitosan	Foliar	Promote fruit yield per tree	Zagzog *et al*., 2017
14	Pomegranate *Punica granatum* L.	Chitosan	Foliar	Promote yield, reduce fruit cracking	Ibtesam *et al*., 2019
15	Quince *Cydonia oblonga* Mill.	PGPR + NPK	Soil	Promote yield and fruit firmness	Gercekcioglu *et al*., 2018
16	Strawberry *Fragaria* spp.	*Bacillus licheniformis*	Root dip and foliar	Promote fruit yield	Kumari *et al*., 2018

6. The stress-alleviating role of biostimulants

Fruit production is affected by many environmental challenges such as drought stress, low and high temperature, salinity, and poor soil quality (Sangiorgio *et al*., 2020). Abiotic stress has been found to reduce the yield by 50 % (Moghaddam and Soleimani, 2012). Biostimulants help plants to tolerate stress by enhancing their internal defense system and supporting physiological and biochemical processes. Certain biostimulants, particularly seaweed extracts, enhance the activity of antioxidant systems by promoting the accumulation of glutathione and ascorbate. Proline production is also enhanced for improving the water regulation, and humic substance helps in soil retention, which is helpful under drought and saline conditions (Rana *et al.,* 2022). Spraying biostimulants on plant leaves increases nitrogen uptake, improves stress resistance, and boosts yields while reducing the need for standard fertilizers (Rossini *et al*., 2025). Seaweed helps to control stress by releasing beneficial proteins, osmoprotectants, and detoxifying enzymes. Even though, the exact mechanism is not fully understood, the likely effect is due to the bioactive compounds in seaweed, such as betaines and cytokinin. Polysaccharides also may act as defense stimulators (Salah *et al*., 2018). Protein hydrolysates contain amino acids like glycine, betaine, and glutamate, which activate the plant defense mechanism. Under salt stress, they enhance the activity of antioxidant enzymes like catalase (CAT) and ascorbate peroxidase (APX), protecting the plant cells from damage (Calvo *et al*., 2014). Humic acid is effective against drought stress; it helps the plant to internally adjust to the stress condition, like osmotic adjustment, and stimulates the production of non enzymatic antioxidant like ascorbate and glutathione, which are degraded during drought (Schiavon *et al*., 2010). Chitosan helps the plant to tolerate salt, drought, and temperature stress. It works by increasing the production of hydrogen peroxide, which acts as a stress signal. This will activate the plant's ROS (reactive oxygen species) scavenging system, boosting the production of protective enzymes such as superoxide dismutase (SOD) and peroxidase (POX) (Qiao *et al*., 2014). However, under field conditions, stress is intermittent, multi factorial, and harder to quantify, which makes it difficult to isolate the biostimulant effect. Studies measuring physiological indicators (proline accumulation, antioxidant enzyme activity, chlorophyll content, and membrane stability) are more reliable than those relying solely on yield data.

7. Biostimulants use for environmental safety and sustainability

The overuse of synthetic agrochemicals in traditional fruit crop cultivation led to environmental concerns for soil erosion, degradation, and the sustainability of agricultural production. Biostimulants are environmentally safe and sustainable as they originate from natural or biological sources, and offer a groundbreaking approach to building sustainable horticultural systems. Using biostimulants in fruit production not only reduces environmental risks but also helps preserve soil microorganisms, protects biodiversity, and assists climate change mitigation (Du Jardin, 2015; Rouphael and Colla, 2020; Khoulati *et al.,* 2025). Biostimulants contribute to sustainable agriculture in several important ways. Their regular use reduces dependence on synthetic fertilizers and pesticides, which in turn lowers energy consumption and greenhouse gas emissions associated with agrochemical production. Beneficial microorganisms such as PGPR, along with humic acids, enhance the ability of plants to absorb nitrogen, phosphorus, and potassium more efficiently, which decreases nutrient losses through runoff and reduces the risk of water body eutrophication. Mycorrhizal inoculants and humic acids also improve the physical and biological condition of the soil by increasing organic matter content, promoting soil aggregation, and enriching microbial diversity. In the face of growing climate challenges, biostimulants strengthen the tolerance of fruit crops to heat, drought, and salinity, thereby contributing to more stable food production. Furthermore, since most biostimulants are compatible with organic certification standards, they serve as practical tools for farmers transitioning toward reduced input and integrated horticultural systems.

7.1 Reduction in agrochemical dependency

Biostimulant's ability to reduce the use of agrochemicals is perhaps the most important of their benefits. Conventional nitrogen fertilizers are associated with nitrate leaching, eutrophication of water bodies, and the release of nitrous oxide (N_2O), a greenhouse gas that has a 298 times higher global warming potential than carbon dioxide in a 100 year time frame (Savci, 2012). Biostimulants such as humic substances and protein hydrolysates have also been shown to improve nitrogen use efficiency (NUE) due to increased activity of enzymes like nitrate reductase and glutamine synthetase, allowing a reduction in the synthetic nitrogen required for maximum crop yield (Colla *et al*., 2015; Canellas and Olivares, 2014). Similarly, plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) promote biological phosphate solubilization and mobilization, which decreases the demand for phosphorus fertilizers, whose mining and application cause contamination from heavy metals and phosphorus leaching into water bodies. Menge *et al.* (1978) found mycorrhizal fungi could substitute phosphorus fertilization in citrus growing, proving the potential for chemical fertiliser reduction. Reduced pesticide application can also be achieved by the biocontrol activity of microbial biostimulants. Biostimulants are not nutrient sources themselves (except for nitrogen fixing bacteria); they enhance nutrient use efficiency, root absorption, and stress resilience. Complete replacement is only feasible in low-productivity systems, organic farming contexts, or when combined with organic manures and compost. Biostimulants, especially microbial inoculants, are vital in maintaining and improving soil biodiversity. Soil microbiomes play a vital role in recycling nutrients, organic matter, maintaining soil structure, and disease suppression. Frequent application of synthetic fertilizers and pesticides alters the microbial population dynamics by eliminating non target beneficial microorganisms and selecting resistant or pathogenic microorganisms (Kopittke *et al.,* 2019).

8. Industrial applications of biostimulant

Industrial biostimulant production encompasses a broad spectrum of techniques. For instance, seaweed extracts are obtained *via* alkaline or enzymatic processing of macroalgae like *Ascophyllum nodosum*, whereas protein hydrolysates are produced through enzymatic digestion of animal or plant proteins to yield amino acid rich products (Craigie, 2011; Colla *et al*., 2015). Microbial variants, which include mycorrhizal fungi and PGPR, are cultivated through controlled fermentation and subsequently formulated into wettable powders or liquid suspensions suitable for broad application (Bashan *et al*., 2014). Additionally, industrially synthesized silicon-based options, such as potassium silicate, are delivered as soil soaks or foliar sprays to improve stress resilience and overall crop quality in commercial agriculture (Savvas and Ntatsi, 2015).

In 2022, the global sector was valued at roughly USD 3.5 billion, with forecasts indicating an 11-13% CAGR (Compound Annual Growth Rate) through 2030. This expansion is underpinned by escalating demand for eco-friendly farming inputs and increasingly stringent regulations concerning synthetic chemicals (Du Jardin, 2015). The sector received a regulatory boost from EU Regulation 2019/1009, which formally classified biostimulants as a distinct fertilizer category, thereby fostering industrial harmonization and facilitating international trade. In response to these dynamics, major agricultural players like BASF, Syngenta, and Valagro have aggressively broadened their biostimulant offerings through strategic acquisitions and heightened R and D spending, further propelling worldwide market adoption.

9. Future prosepects

The demand for the fruit crop, coupled with the necessity for a sustainable system, makes plant biostimulants a pivotal instrument for next-generation agricultural innovation. With increasing challenges such as climate change, soil degradation, and resource limitation, biostimulants offer an eco-friendly alternative to improve crop productivity. Future research should focus on developing crop and stage-specific formulations, as well as understanding their mechanisms of action through advanced tools like genomics, metabolomics, and molecular biology. Integration with precision agriculture technologies can further optimize their application. Further exploration is needed into molecular signaling pathways involving phytohormones, reactive oxygen species (ROS), systemic acquired resistance (SAR), and induced systemic resistance (ISR), the full potential of omics-based techniques including genomics, transcriptomics, proteomics, and metabolomics remains largely unrealized. Integrating biostimulants with precision agriculture technologies including remote sensing, artificial intelligence, decision support systems, and site-specific management tools such integration is rarely implemented in practice. Most biostimulant applications still follow uniform recommendations rather than being dynamically tailored to spatial variability, real-time crop needs, or growth-stage-specific physiological requirements. Bridging this precision gap is critical to optimizing bioavailability, field performance, and resource efficiency. Such approaches are critical for deciphering the intricate regulatory networks and molecular mechanisms that underlie how plants respond to biostimulants. In the absence of a thorough omics-level understanding, the development of biostimulants grounded in rational design will continue to depend on experimentation rather than predictive science.

10. Conclusion

Biostimulant is a promising and sustainable approach for improving growth, productivity, and stress resilience in fruit crops. Biostimulant treatments hold a high potential for enhancing the plant endurance to environmental stress. Both the microbial and non-microbial biostimulants have shown significant potential in improving the yield and quality characteristics by reducing the dependence on agrochemicals. Substances such as humic acids, seaweed extracts, protein hydrolysates, and beneficial microorganisms, including AMF (arbuscular mycorrhizal fungi) and PGPR (plant growth promoting rhizobacteria), have consistently shown positive effects on both vegetative and reproductive parameters. Their applications not only boost productivity but also contribute to better fruit quality attributes such as size, sugar, antioxidant, and shelf-life. Additionally, biostimulants support sustainable agriculture by reducing reliance on chemical fertilizers and improving soil health. To maximize the effect, it is essential to optimize application rates and crop specific recommendations based on stages and environmental conditions. Moreover, a deeper understanding of the interaction and combined effect of different biostimulants is required. Based on the breadth and consistency of evidence across fruit crops, seaweed extracts (particularly *Ascophyllum nodosum* based products) and plant growth promoting rhizobacteria (PGPR) emerge as the most promising categories. Seaweed extracts show reliable improvements in fruit quality, flowering, and abiotic stress tolerance across multiple fruit crop systems. PGPR especially *Bacillus* spp. and *Pseudomonas fluorescens* demonstrate consistent yield improvement, improved phosphorus solubilization, and induced systemic resistance. Humic and fulvic acids show strong supporting evidence as soil conditioners and root growth promoters.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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