

Natural Biostimulants for Improving Quality and Shelf-Life of Temperate Fruits

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Natural biostimulants are sustainable tools derived from biological origins, such as seaweed extracts, humic substances, and beneficial microbes, which enhance temperate fruit quality and shelf-life. They act by improving nutrient use efficiency, boosting antioxidant systems, regulating ethylene, and strengthening plant defenses against stress. This reduces reliance on chemical inputs, supports sustainable agriculture, and helps maintain fruit firmness, nutritional value, and marketability post-harvest. Despite regulatory and efficacy challenges, biostimulants present a promising future for resilient and high-quality fruit production.

Introduction

The growing global demand for sustainable agriculture practices, coupled with the need to reduce chemical inputs while maintaining high crop quality, has brought natural biostimulants to the forefront of agricultural innovation. Temperate fruits, such as apples, peaches, pears, plums, and cherries, are economically significant and vital for human nutrition. However, their quality and post-harvest longevity are frequently threatened by environmental stresses, conventional farming techniques, and pathogen attacks. Natural biostimulants present a promising solution by enhancing plant health, optimizing nutrient uptake, boosting stress tolerance, and ultimately, improving fruit quality and extending shelf-life. These advancements align with contemporary goals for agricultural sustainability and efficiency. This article will explore the concept, types, mechanisms, and specific impacts of natural biostimulants on temperate fruits, alongside their advantages, limitations, and future outlook within the context of sustainable fruit production. Studies have underscored the importance of biostimulants in temperate fruit growing, although further research is needed regarding their impact on stress mitigation. Biostimulants, encompassing organic compounds and microbes, regulate plant growth through molecular, physiological, and biochemical changes, thereby helping plants mitigate the effects of climate change. This unique mode of action positions them as a key component in fostering sustainable agriculture, especially as climate-related challenges intensify. Plant biostimulants enhance crop quality by promoting plant health and vigor, and they can also increase harvestable yields, contributing to meeting global food demand while promoting planetary health (Melini *et al.*, 2023 & Robinson, 2025).

Concept of Biostimulants

Definition and scope: A biostimulant is defined as a formulated product of biological origin that improves plant productivity due to the novel or emergent properties of its complex constituents, an effect not solely attributed to essential plant nutrients, plant growth regulators, or plant protective compounds. This definition highlights that biostimulants modulate biological function positively through molecules or mixtures of molecules for which an explicit mode of action may not be fully defined. The Environmental Protection Agency (EPA) defines plant biostimulants as products containing naturally occurring substances, microorganisms, or their synthetic equivalents that stimulate natural processes to improve nutrient uptake, nutrient efficiency, abiotic stress tolerance, or crop quality and yield. A proposed US regulatory definition describes them as substances or microorganisms that, when applied to seeds, plants, the rhizosphere, soil, or other growth media, support a plant's natural processes independently of their nutrient content, including improving nutrient availability, uptake, or use efficiency, tolerance to abiotic stress, and consequent growth, development, quality, or yield. Biostimulants are naturally derived substances that enhance plant growth, nutrient use efficiency, crop yield, quality, health, and tolerance to abiotic stress. Organic acids are crucial components, as they enhance nutrient availability and improve soil structure (Cancellier, 2025; Melini *et al.*, 2023).

Biostimulants vs. biofertilizers and pesticides: Biostimulants are distinct from both fertilizers and pesticides. Unlike fertilizers, which primarily provide nutrients directly to plants, biostimulants work by stimulating the plant's internal systems and natural processes to improve nutrient use efficiency, stress tolerance, and overall plant health. They are not classified as pesticides because they do not possess a defensive character against pathogens and therefore do not directly control pests or diseases. Instead, biostimulants enhance natural processes like root development, nutrient uptake, and stress resilience, thus supporting overall plant health. They include diverse products such as microbial inoculants, enzymes, seaweed extract, amino acids, and humic substances, influencing plant growth through various mechanisms. While a "biostimulant fertilizer" can combine primary macronutrients with biostimulating components like humic acids or seaweed extracts to improve root development and nutrient absorption, the core function of biostimulants remains distinct from direct nutrient provision or pest control. Their unique role is to activate the plant's natural abilities to grow and thrive. (Du Jardin, 2015; Cristofano *et al.*, 2021 & Baltazar *et al.*, 2021)

Mechanism of action: Biostimulants are effective in inducing physiological processes in plants that enhance their growth and acclimation to stress. They operate by stimulating plant growth, enhancing nutrient uptake, improving stress tolerance, and boosting overall plant health. Research on biostimulant mechanisms requires understanding the complex composition and bioactive ingredients of these substances. Biostimulants enhance plant growth and health by improving nutrient uptake and increasing resilience to stresses such as heat and drought, effectively helping plants absorb nutrients rather than directly supplying them. They can stimulate soil microbial activity, leading to improved nutrient mobilization and uptake. This leads to benefits such as improved crop yield and quality, increased resistance to abiotic and biotic stress, enhanced root development, and improved soil health. Many types of agricultural biostimulants are approved for organic farming. The application of humic substances (HS), a type of biostimulant, can improve various plant growth parameters, including increasing the content of photosynthetic pigments, carotenoids, total phenols, flavonoids, and the uptake of NPK (nitrogen, phosphorus, potassium). Similarly, glycine betaine and proline have been shown to increase plant tolerance to various environmental stresses, such as freezing, salinity, drought, and oxidative stress. Biostimulants play a vital role in promoting sustainability by reducing the need for chemical fertilizers and pesticides, promoting beneficial microbial activity, supporting regenerative agricultural practices, and ultimately increasing productivity and return on investment for growers (Cancellier, 2025; Robinson, 2025 & Martínez-Lorente *et al.*, 2024).

Types of Natural Biostimulants

Natural biostimulants encompass a diverse group of substances and microorganisms that enhance plant growth and development, improve nutrient use efficiency, and increase tolerance to abiotic stress. They are crucial for sustainable fruit cultivation by promoting plant health and vigor, and many are approved for organic farming systems. Organic crop stimulants (OCSs) are particularly promising for enhancing abiotic stress tolerance and crop productivity. Biostimulants play a crucial role in enhancing the anatomical, morphological, and physiological traits of fruit crops (Kumar *et al.*, 2025; Melini *et al.*, 2023 & Robinson, 2025).

Seaweed extracts: Seaweed extracts, particularly from *Ascophyllum nodosum*, are widely recognized as effective biostimulants. These extracts are rich in bioactive compounds such as phytohormones (e.g., auxins, cytokinins, gibberellins), polysaccharides, proteins, polyphenols, and vitamins. They enhance plant growth and stress tolerance under both optimal and stressful conditions, improving nutrient uptake and overall plant health. Seaweed extracts have been shown to increase fruit production and improve fruit quality by contributing to the content of phenolic compounds and antioxidant activity (Pereira *et al.*, 2023; Kinhal, 2023 & Kumari *et al.*, 2022a).

Humic and fulvic acids: Humic and fulvic acids are vital components of soil organic matter that function as powerful biostimulants. They significantly improve soil health and plant growth by enhancing nutrient availability and uptake, stimulating root development, and improving soil structure. Their application can increase various plant growth parameters, including photosynthetic pigment content, total phenols, flavonoids, and the uptake of essential nutrients like nitrogen, phosphorus, and potassium (Baltazar, 2021 & Whitney, 2024).

Protein hydrolysates and amino acids: Protein hydrolysates and amino acids are derived from protein breakdown and serve as crucial biostimulants. These compounds act as readily available nitrogen sources and signaling molecules, enhancing plant growth, improving nutrient use efficiency, and increasing stress resilience. They contribute to better crop yields and overall plant vigor (Whitney, 2024).

Chitosan: Chitosan, a polysaccharide derived from chitin, is known for its biostimulant properties. It can induce plant defense mechanisms, enhance nutrient uptake, and promote overall plant growth and development. Chitosan also plays a role in improving resistance to biotic and abiotic stresses (Shahid, 2023).

Plant extracts (Moringa, Neem, Aloe vera, etc.): Various plant extracts, such as those from Moringa, Neem, and Aloe vera, are increasingly utilized as biostimulants. These extracts contain a complex mixture of compounds that can enhance plant growth, yield, and resilience to stress. They contribute to improved plant health and productivity through diverse mechanisms (Whitney, 2024).

Beneficial microorganisms (PGPR, mycorrhizae, yeasts): Beneficial microorganisms, including Plant Growth-Promoting Rhizobacteria (PGPR), mycorrhizal fungi, and yeasts, act as potent biostimulants. PGPR enhance nutrient availability and uptake, produce phytohormones, and suppress plant pathogens. Mycorrhizal fungi form symbiotic relationships with plant roots, improving water and nutrient absorption, particularly phosphorus. Yeasts can also stimulate plant growth and enhance resistance to stresses. These microbial inoculants improve soil health, stimulate natural processes, and enhance nutrient use efficiency, directly contributing to improved crop quality and yield. (Melini *et al.*, 2023 & Meena *et al.*, 2025)

Mechanisms of Quality Improvement

Biostimulants enhance fruit quality through a range of interconnected physiological and biochemical mechanisms. These actions lead to improved fruit characteristics that are desirable for both consumers and producers.

Enhancement of antioxidant systems: Biostimulants can significantly enhance the antioxidant defense systems in fruits. This involves increasing the activity of key antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), as well as elevating the levels of non-enzymatic antioxidants like ascorbic acid (Vitamin C), carotenoids, and phenolic compounds. These antioxidants scavenge reactive oxygen species (ROS), thereby mitigating oxidative stress caused by environmental factors (e.g., UV radiation, temperature fluctuations) and delaying fruit senescence. Enhanced antioxidant capacity contributes to better fruit quality, color, and nutritional value, and also plays a role in extending shelf-life by reducing oxidative damage post-harvest (Calvo *et al.*, 2014).

Regulation of ethylene production and respiration: Ethylene is a crucial phytohormone that regulates fruit ripening and senescence, particularly in climacteric fruits like apples, peaches, and plums. Biostimulants can modulate ethylene biosynthesis pathways, leading to reduced ethylene production rates. Concurrently, they can also influence fruit respiration rates. By lowering both ethylene production and respiration, biostimulants can slow down the ripening process, thereby extending the on-tree and post-harvest life of fruits, maintaining firmness, and delaying undesirable changes in texture and flavor. This regulatory effect is critical for improving the storage potential of temperate fruits (Boutahiri *et al.*, 2024).

Maintenance of cell wall integrity: The structural integrity of fruit cell walls is paramount for maintaining firmness, texture, and resistance to mechanical damage and pathogen invasion. Biostimulants, especially those containing elements like silicon or calcium, can strengthen cell wall components (e.g., pectin, cellulose, hemicellulose). This leads to firmer fruits that are less susceptible to bruising, softening, and water loss during storage and transport. Maintaining cell wall integrity directly translates to improved fruit quality and extended marketability (Whitney, 2024).

Induction of defense-related enzymes: Natural biostimulants can prime the fruit's natural defense mechanisms by inducing the activity of various defense-related enzymes. These enzymes, such as chitinases, β -1,3-glucanases, and phenylalanine ammonia-lyase (PAL), are involved in systemic acquired resistance (SAR) or induced systemic resistance (ISR). By enhancing these enzymatic activities, biostimulants bolster the fruit's ability to resist fungal and bacterial pathogens, reducing post-harvest decay and preserving fruit quality for longer durations.

Improved nutrient and metabolite accumulation: Biostimulants facilitate more efficient uptake and assimilation of essential macro and micronutrients by fruit trees. This improved nutrient use efficiency directly impacts fruit composition, leading to higher accumulation of sugars, organic acids, vitamins, and other beneficial secondary metabolites. These metabolic changes contribute to enhanced flavor, sweetness, aroma, and overall nutritional value, which are key indicators of fruit quality. Furthermore, balanced nutrient status can lead to stronger, healthier fruits with improved physiological functions that contribute to extended shelf-life (Petri *et al.*, 2019).

Impact on Shelf-Life of Temperate Fruits

Biostimulants are increasingly recognized for their positive impact on the shelf-life of temperate fruits, playing a crucial role in minimizing post-harvest losses and maintaining fruit quality (Boutahiri *et al.*, 2024).

Effects on apple: Biostimulants have shown promise in enhancing the shelf-life and quality of apples. Studies indicate that biostimulant technology can lead to greater firmness in apple trees compared to standard fertilization programs. Certain biostimulants containing mineral nutrients like zinc and silicon can contribute to strengthening the cell wall structure in apples, which is directly linked to fruit quality and storage potential (Whitney, 2024). Research on 'Red Delicious' apples in temperate regions has explored the efficacy of commercial biostimulants containing seaweed extract, amino acids, herbal extract, and humic acid on fruit yield and quality attributes (Quinn, 2025). Detailed research has also examined the impact of various biostimulant types on Annurca apple quality from harvest through storage, demonstrating their potential to improve total soluble solids (TSS), total acidity (TA), pH,

and flesh firmness (Agrithority, 2024; (Graziani *et al.*, 2020). Furthermore, biostimulants have been found to significantly reduce the incidence of physiological disorders like "Jonathan spot" in apples after prolonged storage, indicating a direct positive effect on shelf-life (Soppelsa *et al.*, 2020). A study in Namiquipa, Chihuahua, evaluated the effect of biostimulants on the fruit quality of 'Golden Glory' apples in the 2023 season (Acevedo-Barrera *et al.*, 2024). Ultimately, biostimulants aid in maintaining apple quality longer, thereby extending their shelf-life.

Effects on peach: While specific recent studies on biostimulants' direct impact on peach shelf-life were not extensively detailed in the provided extracts, general principles suggest that biostimulants' ability to regulate ethylene production, reduce respiration, enhance antioxidant systems, and maintain cell wall integrity would be beneficial for peaches, a climacteric fruit. These mechanisms collectively contribute to delayed ripening, reduced softening, and improved resistance to spoilage, which are all crucial for extending the shelf-life of peaches.

Effects on pear: For pears, biostimulants contribute to extending shelf-life by influencing fruit maturation and overall quality. Seaweed-based biostimulants have the potential to impact fruit maturation, which in turn influences postharvest quality (Zhi and Dong, 2024). An enzymatic hydrolysate of Fabaceae, a plant-derived biostimulant, has been shown to increase the shelf-life of fruits and vegetables, including pears, due to its high concentration of natural triacontanol and vitamins, specifically B6. Preharvest application of Gamma-aminobutyric acid (GABA) as a biostimulant has also been shown to enhance the shelf-life of lemon fruit, and similar benefits can be inferred for pears by extension of its general mechanisms (Elzayat *et al.*, 2024).

Effects on plum and cherry: New-generation plant growth regulators, including biostimulants, are noted to prolong the shelf life of certain fruits and help minimize post-harvest losses, which would include plums and cherries (Bautahiri *et al.*, 2024). Specifically for sweet cherries, biostimulant treatments have been shown to improve bud breakage, enhance flowering, and advance ripening, while also leading to an improvement in fruit quality and organoleptic profile (García-Cano *et al.*, 2025a; Jacobs, 2025). Most biostimulant treatments have exhibited a positive influence on sweet cherry fruit quality traits, although responses can vary by treatment (Estiveira, 2023; Afonso *et al.*, 2023). For plums, the application of spermidine significantly improved the preservation of organic acids and polyphenols during cold storage, directly extending their shelf-life (Gundogdu *et al.*, 2024). For fruits stored at 4 °C, a mixture of biostimulants demonstrated increased flesh resistance and a reduced rate of weight loss, which are direct indicators of extended shelf-life for fruits like plums and cherries (Cancellier, 2024).

Advantages over Conventional Chemicals

Natural biostimulants offer several significant advantages over conventional chemical inputs in fruit production, aligning with a new era of sustainable agriculture. They provide a path toward more sustainable and environmentally friendly agricultural practices, contributing to meeting global food demand while promoting planetary health (Mannino, 2023).

Firstly, biostimulants directly stimulate plant and microbial processes using live microbes or bioactive compounds, leading to improved plant growth, increased resilience, and boosted productivity. This contrasts with enhanced nutrient fertilizers that primarily feed soil microbes. Examples of biostimulating substances include molasses, yeast extract, organic acids, amino acids, and plant extracts (Cancellier, 2025).

Secondly, biostimulants activate processes in the soil or within the plant to improve nutrient availability, enhance tolerance to abiotic stresses, increase yield, and improve crop quality. They do not directly supply nutrients like fertilizers but rather enhance the plant's natural processes, as defined by the US 2018 Farm Bill. They achieve this by enhancing root growth and soil interaction, which leads to more efficient nutrient absorption by plants (Bulgari *et al.*, 2015).

Thirdly, biostimulants are a cost-effective alternative to conventional inputs, reducing the need for synthetic fertilizers (Boutahiri *et al.*, 2024). An organic biostimulant demonstrated a more pronounced effect on cucumber plants compared to a non-organic counterpart, significantly promoting lateral root development and inhibiting primary root elongation, resulting in a 122% increase in root volume and a 42% increase in root ramifications. This indicates that organic biostimulants can lead to superior plant growth responses (García-Cano *et al.*, 2025b). These benefits highlight their potential to reduce the ecological footprint of agriculture while maintaining or even improving crop performance.

Limitations and Challenges

Despite the numerous benefits, the widespread adoption and consistent efficacy of natural biostimulants in fruit production face several limitations and challenges.

A significant hurdle is the lack of standardized methodologies or processes for the independent validation of their efficacy. The effectiveness of biostimulants can be highly variable, influenced by factors such as the specific preparation, dose, concentration, application method, plant species and cultivar, and environmental conditions. Different crops often respond differently to biostimulants, contributing to this inconsistency (Handoko and Lin, 2025; Soppelsa *et al.*, 2020).

From a regulatory standpoint, the biostimulant industry requires a clear, consistent, and predictable process for market entry, along with clarity on product claims and global harmonization of standards and practices. There is a pressing need for uniform enforcement of regulations at state and federal levels, and a clear approach for the registration of active ingredients that may have dual use (i.e., possessing both plant health properties and pesticide action). Legislative efforts, such as the Plant Biostimulant Act, aim to create a uniform federal definition and a consistent regulatory pathway to market to facilitate farmers' access to these products and stimulate further research and development (Giannakoula *et al.*, 2024; Pereira *et al.*, 2024).

Furthermore, the propagation of some microbial biostimulants, such as arbuscular mycorrhizal fungi (AMFs), is complicated by their biotrophic character (Kumari *et al.*, 2022b). Additionally, natural organic fertilizers, a category that shares similar sourcing and processing challenges with natural biostimulants, often suffer from high cost and limited availability, which can also apply to certain natural biostimulant products. These challenges underscore the need for more robust research, standardized testing, and clearer regulatory frameworks to fully harness the potential of natural biostimulants.

Future Prospects

The future prospects for natural biostimulants in fruit production are exceedingly promising, fueled by expanding market awareness, continuous technological advancements, and supportive regulatory frameworks. The biostimulants market is currently experiencing rapid growth, with ongoing analysis focusing on active ingredients such as humic substances, seaweed extracts, amino acids, microbial amendments, and minerals & vitamins. This growth also considers various crop types, modes of application, and product forms (dry or liquid), with global forecasts extending to 2029 (Ciriello *et al.*, 2025; Patanè *et al.*, 2025).

Key types of natural biostimulants are expected to continue their ascent. Humic and fulvic acids are valued for their ability to improve soil health and plant growth, while seaweed extracts are recognized for enhancing plant growth, improving crop resilience, and boosting soil health. Amino acids and peptides demonstrate significant potential for increasing crop yields and improving stress resilience. Plant extract-based biostimulants, derived from various botanical sources, are increasingly being employed to enhance plant growth, yield, and stress resilience (Graziani *et al.*, 2020).

Future developments will likely concentrate on gaining a deeper understanding of the molecular mechanisms of action of these biostimulants, leading to more targeted and efficient formulations. This enhanced understanding is crucial for achieving consistent and predictable results across diverse agricultural environments. The application of microbial plant

biostimulants in fruit and horticultural crops is also gaining considerable attention, particularly for its positive impact on product quality. As research progresses, there will be an increased focus on integrating biostimulants into comprehensive sustainable agriculture systems, thereby further reducing reliance on conventional chemical inputs and ensuring both high-quality produce and environmental stewardship for temperate fruits.

Conclusion

Natural biostimulants offer a transformative and sustainable approach to enhancing the quality and shelf-life of temperate fruits. By harnessing inherent biological processes, these substances effectively improve nutrient use efficiency, bolster stress tolerance, and activate defense mechanisms within fruit plants. The diverse array of natural biostimulants—including seaweed extracts, humic and fulvic acids, protein hydrolysates, chitosan, various plant extracts, and beneficial microorganisms—each contribute to superior fruit quality through specific mechanisms. These mechanisms encompass enhanced antioxidant systems, regulated ethylene production, strengthened cell wall integrity, induced defense enzymes, and optimized nutrient and metabolite accumulation. While these biostimulants present significant advantages over conventional chemical inputs by promoting sustainable agricultural practices and reducing environmental impact, challenges persist. These include issues related to regulatory clarity, variability in efficacy, and the need for standardized validation methodologies. Despite these hurdles, the expanding market, ongoing scientific advancements, and a growing demand for sustainable agricultural solutions point to a highly promising future for natural biostimulants in fruit production. Continued investment in research and development, coupled with the establishment of harmonized regulatory frameworks, will be crucial in unlocking their full potential. This will ensure the resilient, high-quality, and environmentally sound production of temperate fruits for future generations.

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