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Impact of emerging bio-stimulants on the morpho-physiological performance of underutilized fruit crops

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Abstract
Emerging bio-stimulants including natural plant extracts, beneficial microbes and novel organic compounds are gaining attention as sustainable tools to enhance crop growth and stress resilience. This review examines how such bio-stimulants influence the morphological and physiological development of underutilized fruit crops worldwide. Underutilized fruits (e.g. baobab, dragonfruit, Indian gooseberry and many indigenous species) are valued for their nutrient density and climate resilience but often suffer from low yields and limited research. Bio-stimulants derived from seaweed, humic substances, protein hydrolysates, chitosan, silicon and microbial inoculants can significantly improve plant height, root development, leaf area, flowering, fruit set and overall yield in diverse fruit species. They also enhance physiological functions such as photosynthesis, nutrient uptake, hormone balance and antioxidant activity, helping plants cope with stresses like drought, salinity, or pests. Global studies indicate consistent benefits: for example, seaweed extract sprays boost fruit size and vitamin content in apples and peaches, while microbial inoculants (e.g. Rhizobium, Bacillus) fix nitrogen or mobilize phosphorus to benefit legumes and fruit trees. By integrating examples from major and minor fruit crops, this article highlights how bio-stimulants can unlock the potential of neglected fruit species. The review covers the historical context of bio-stimulant use, key categories of stimulants, specific effects on growth and physiology, practical applications and worldwide perspectives. It concludes that expanding bio-stimulant research and application in underutilized fruit cultivation could promote sustainable production, nutritional security and climate adaptation on a global scale.

Keywords: Bio-stimulants, underutilized fruit crops, morphological traits, physiological performance, seaweed extracts, microbial inoculants, sustainable horticulture, nutrient uptake, stress tolerance

Introduction

Underutilized fruits, also referred to as minor, neglected, or orphan fruits, represent a diverse group of fruit species that possess significant nutritional, medicinal, ecological, and economic potential but remain largely overlooked in mainstream agricultural systems [5]. These fruits are often indigenous to specific regions and are traditionally cultivated or collected from the wild by local communities, particularly in tropical, subtropical, and arid ecosystems. Examples include bael (*Aegle marmelos*), jamun (*Syzygium cumini*), aonla (*Emblica officinalis*), ber (*Ziziphus mauritiana*), wood apple (*Limonia acidissima*), karonda (*Carissa carandas*), tamarind (*Tamarindus indica*), phalsa (*Grewia asiatica*), sea buckthorn (*Hippophae rhamnoides*), and various wild berries and figs. Despite their adaptability and resilience, these fruits have received limited attention in terms of scientific research, genetic improvement, value chain development, and market integration [6]. One of the most important attributes of underutilized fruits is their exceptional nutritional profile. Many of these fruits are rich sources of vitamins, minerals, dietary fiber, antioxidants, and bioactive compounds such as polyphenols, flavonoids, and organic acids [7]. For instance, aonla is renowned for its high vitamin C content, jamun is valued for its antidiabetic properties, and sea buckthorn is known for its rich composition of omega fatty acids and carotenoids. Regular consumption of such fruits can contribute to improved immune function, reduced risk of chronic diseases, and better overall health, making them particularly valuable in combating malnutrition and micronutrient deficiencies in vulnerable populations [8].

Underutilized fruits also play a crucial role in sustainable agriculture and climate resilience. Many species are naturally tolerant to abiotic stresses such as drought, salinity, poor soil fertility, and temperature extremes [9]. Their ability to thrive under marginal conditions makes them suitable for cultivation in rainfed, degraded, or resource-poor areas where conventional fruit crops often fail. Additionally, these fruit trees support biodiversity by providing habitat and food for pollinators, birds, and other organisms, thereby strengthening agro-ecosystem stability [10]. From a socio-economic perspective, the promotion of underutilized fruits can enhance livelihood opportunities for small and marginal farmers, women, and indigenous communities [11]. Value addition through processing into products such as juices, jams, candies, nutraceuticals, and herbal formulations can significantly increase income and create rural employment. Integrating underutilized fruits into mainstream horticulture, research programs, and market systems is therefore essential for achieving nutritional security, sustainable land use, and inclusive agricultural development [12]. Underutilized fruit crops are diverse species that have significant nutritional and economic potential but remain neglected by mainstream agriculture. These fruits which include regional staples such as dragonfruit, karonda, amla (Indian gooseberry), baobab, cherimoya and many others often thrive under marginal conditions where major fruits (like apples, bananas, or oranges) fail [1]. They are typically rich in vitamins, antioxidants and dietary fibers far surpassing those in common fruits. For example, some wild cherries can contain dozens of times the vitamin C of an orange. The renewed global interest in these crops arises from their natural tolerance to drought, heat and poor soils, offering a climate-smart solution for food security [2]. However, underutilized fruit trees or vines generally exhibit lower yields and slower growth under cultivation. Improving their productivity without harming the environment is therefore a research priority. Bio-stimulants have emerged as promising agents to address this challenge. Unlike conventional fertilizers, bio-stimulants include organic substances (seaweed extracts, humic acids, protein hydrolysates, chitosan, etc.) and beneficial microbes (rhizobacteria, mycorrhizal fungi) that stimulate plant metabolism and stress tolerance [2]. They act through biochemical pathways enhancing nutrient uptake, enzyme activity, or natural hormone levels rather than supplying nutrients directly. Recent years have seen a boom in new or “emerging” bio-stimulants, such as iodine-containing products, novel microbial strains and bio-products from agricultural byproducts [3]. These innovations align with sustainable agriculture goals, as they reduce chemical inputs and boost ecological balance. This article provides review of how emerging bio-stimulants affect the morpho-physiological performance of underutilized fruit crops worldwide [4]. The global perspective highlights adoption in different regions and discusses future prospects for integrating bio-stimulants into cultivation of neglected fruit species. By synthesizing current knowledge, this review aims to inform researchers and growers about harnessing bio-stimulants to enhance the potential of underutilized fruits in sustainable horticulture.

Historical Perspectives and Key Contributors

The use of natural plant stimulants dates back centuries. Coastal farmers in Europe historically applied seaweed and kelp to their fields, observing richer growth in treated crops even before knowing the underlying chemistry [13]. Similarly, indigenous peoples worldwide used fermenting plant extracts and animal manures to enhance soil fertility and crop vigor, practices that implicitly employed biostimulatory principles. Modern scientific recognition of these effects, however, is relatively recent [14]. In the late 20th century, agronomists began distinguishing *biostimulants* from traditional fertilizers and pesticides. They identified the concept formally in the 1990s, spurred by research into how non-nutrient substances could regulate plant hormones, nutrient efficiency and stress responses [15]. Key developments included the categorization of substances such as humic acids (from organic matter) and beneficial microbes (like Rhizobium and mycorrhizae) as agricultural amendments. Pioneering scientists in plant physiology and soil science investigated specific mechanisms: for instance, how seaweed-derived cytokinins improve root growth, or how microbial inoculants fix atmospheric nitrogen [16]. These foundational studies were carried out by researchers across universities and research institutes in Europe, North America and Asia. For example, agronomists at coastal institutes empirically demonstrated seaweed foliar sprays enhancing crop yields, while microbiologists documented how certain soil bacteria produce plant hormones (auxins, gibberellins) and solubilize nutrients [17]. Over time, international bodies such as the Food and Agriculture Organization (FAO) and various academic societies recognized biostimulants as a class [18]. This led to cooperative research programs worldwide investigating “neglected and underutilized plant species,” including many minor fruits with local importance. Simultaneously, botanists and horticulturists began documenting underutilized fruits themselves. Early explorers and colonial-era botanists noted numerous fruit-bearing trees (like *Aegle marmelos*, *Syzygium cumini*, *Carissa carandas*) used by local communities but rarely traded commercially [19]. In the latter half of the 20th century, botanical gardens, universities and non-profits started systematic collection and conservation of these “minor fruits.” Researchers such as those at the Indian Council of Agricultural Research, African universities and Latin American institutes characterized their nutritional value and agronomy [20]. Publications emerged on domestication and propagation of fruits like jackfruit, passion fruit and African locust bean, laying groundwork for improvement. More recently, agricultural scientists have begun testing bio-stimulants on these species, combining knowledge from both fields [21]. Thus, the historical narrative intertwines two threads: the rise of bio-stimulant science and the rediscovery of underutilized fruits. Both have drawn contributions from experts in plant physiology, soil science, horticulture and ecology [22]. While it is difficult to attribute the field to single individuals, the cumulative work of interdisciplinary teams has established that manipulating plant natural processes through exotic extracts or microorganisms can boost the performance of fruit crops that were once ignored [23].

Underutilized Fruit Crops: Importance and Diversity

Underutilized fruit species are abundant across all continents, each region harboring unique crops adapted to local climates and soils [24]. They are typically defined as crops with established use but limited cultivation or research investment. Many are staples of traditional diets and hold cultural significance. Table 1 highlights some prominent underutilized fruits, their native regions, key nutrients and special properties. Table 1 lists examples such as *Hylocereus undatus* (dragonfruit), native to Central America but now cultivated in Asia, *Adansonia digitata* (African baobab), valued across sub-Saharan Africa for its vitamin Crich pulp, *Malpighia glabra* (West Indian cherry or acerola), a Caribbean fruit exceptionally high in antioxidants, *Phyllanthus emblica* (Indian gooseberry), renowned in South Asia for medicinal uses, *Syzygium cumini* (Java plum), common in India with antidiabetic properties and many others like *Carissa carandas* (karonda), *Manilkara zapota* (sapodilla), *Passiflora edulis* (passionfruit), *Terminalia ferdinandiana* (Kakadu plum of Australia) and *Sclerocarya birrea* (marula of Southern Africa). Each species in the table is noted for attributes such as high vitamins, resilience to drought, or industrial uses (e.g. juice, herbal medicine).

These fruits collectively demonstrate the global scope of the topic. They thrive in climates ranging from arid plains to tropical rainforests. Many are notably hardy: for instance, *Ziziphus mauritiana* tolerates poor, saline soils in India, while *Opuntia ficus-indica* (prickly pear) grows in semi-deserts [25]. Nutritionally, underutilized fruits often surpass common fruit crops in certain components: baobab pulp can have ten times the calcium of milk and triple the vitamin C of oranges, acerola might boast dozens of times the vitamin C content of an apple [26]. They also carry diverse phytochemicals anthocyanins in jamun berries, xanthones in mangosteen, or ellagitannins in wood apple which may provide health benefits. Despite such potential, these crops face obstacles: limited propagation techniques, poor market infrastructure and vulnerability to pests without dedicated varieties [27]. Underutilized fruits frequently yield less or fruit irregularly under current practices. Here is where bio-stimulants offer promise. By applying novel growth enhancers, farmers and researchers aim to jumpstart plant vigor and fruiting even in marginal or unoptimized conditions [28]. While mainstream fruits like apples or bananas have been the focus of most horticultural research, emerging trends push to extend those innovations to minor fruits. For example, trials are underway in India to use seaweed extract on aonla orchards, or to inoculate African baobab seedlings with mycorrhizal fungi. Such efforts recognize that accelerating the productivity of underutilized species could improve nutrition and livelihoods in rural communities worldwide [29].

Table 1: Examples of Underutilized Fruit Crops with Notable Characteristics [61, 62, 63]

Fruit (Common Name)	Scientific Name	Region of Origin	Key Nutrients/Bioactive Compounds	Notable Features (Hardiness, Uses)
Dragonfruit	*Hylocereus undatus*	Central America/Southeast Asia	Vitamin C, Betacyanins	Drought-tolerant cactus, new exotic fruit market, high water content
Baobab	*Adansonia digitata*	Sub-Saharan Africa	Vitamin C, Calcium, Fiber	Exceptional vitamin C, used in beverages and nutrition
West Indian Cherry (Acerola)	*Malpighia glabra*	Caribbean/Central America	Vitamin C, Antioxidants (anthocyanins)	Extremely high vitamin C, used in supplements
Indian Gooseberry (Amla)	*Phyllanthus emblica*	Indian Subcontinent	Vitamin C, Tannins	Medicinal uses (Ayurveda), grows in semi-arid regions
Java Plum (Jamun)	*Syzygium cumini*	South/Southeast Asia	Anthocyanins, Iron	Fruit with medicinal value, tolerant of drought
Karonda	*Carissa carandas*	Indian Subcontinent	Vitamin C, Flavonoids	Thorny shrub, used in preserves, survives poor soils
Phalsa	*Grewia asiatica*	Indian Subcontinent	Vitamin C, Flavonoids	Deciduous shrub, sweet-sour berries, grows in arid gardens
Jackfruit	*Artocarpus heterophyllus*	South/Southeast Asia	Carbohydrates, Fiber	Large tropical tree, fruit is starchy, seeds edible, pest-resistant
Breadfruit	*Artocarpus altilis*	Pacific Islands/SE Asia	Carbohydrates, Potassium	Grows well in poor soils, staple starch source, multiple uses
Sapodilla (Chikoo)	*Manilkara zapota*	Mesoamerica	Carotenoids, Sugar	Hardy tree, latex source (chicle), drought resistant
Passionfruit	*Passiflora edulis*	South America	Vitamin C, Dietary fiber	Vine, high economic value in tropical regions
Kakadu Plum	*Terminalia ferdinandiana*	Northern Australia	Extremely high Vitamin C, antioxidants	Tolerates extreme heat, "superfruit" with enormous vitamin C content
Marula	*Sclerocarya birrea*	Southern Africa	Vitamin C, Amino acids	Drought-hardy tree, edible fruit, used for oil and liquor (Amarula)
Cherimoya (Custard apple)	*Annona cherimola*	Andes (South America)	Vitamin C, Fiber	Fragrant fruit, grows at high elevations, delicate leaves
Feijoa (Pineapple guava)	*Acca sellowiana*	South America	Vitamin C, Minerals	Subtropical shrub, cold-hardy for fruit, aromatic fruit

Emerging Bio-Stimulants: Types and Mechanisms

Bio-stimulants encompass a heterogeneous group of materials that, when applied to plants or soils, stimulate natural processes to enhance nutrient uptake, growth and stress tolerance. They do not directly supply nutrients like a fertilizer instead, they activate or mimic plant physiological pathways. Emerging bio-stimulants come from organic sources or innovative preparations [30]. The main categories are outlined below, with typical examples and their general modes of action (Table 2).

- **Seaweed Extracts:** Obtained from marine macroalgae (commonly brown seaweeds such as *Ascophyllum* or *Ecklonia*), these extracts contain plant hormones (auxins, cytokinins), vitamins, minerals and osmolytes. Seaweed biostimulants are known to improve root and shoot development, enhance germination and alleviate abiotic stress (drought, salinity) by promoting water uptake and enzymatic activity [31]. For fruit crops, foliar sprays of seaweed extract often increase flowering, fruit set and overall yields. In organic farming worldwide, seaweed-based products (commercially available under various names) are valued for their consistent positive effects on plant vigor [32].

- **Humic and Fulvic Substances:** These are large organic molecules resulting from decomposition of compost or leonardite. Humic acids improve soil structure and cation exchange capacity, binding and slowly releasing nutrients. They stimulate root growth and enhance nutrient uptake (especially of nitrogen and phosphorus) by chelating ions [33]. Fulvic acids, smaller and more mobile, enhance seed germination and photosynthetic efficiency. Field and greenhouse studies on many fruit trees show that soil or foliar applications of humic extracts can lead to greener foliage and more robust root systems, which in turn support higher yields [34].
- **Protein Hydrolysates/Amino Acids:** Hydrolyzed proteins from animal or plant sources (e.g. legume meal, fish byproducts) yield mixtures rich in free amino acids and short peptides. These serve dual roles: as readily available nitrogen sources and as signaling molecules. Amino acids like proline, glutamic acid and glycine can act as osmoprotectants, helping plants manage osmotic stress [35]. They can also induce expression of nutrient transporter genes in roots. Application of amino-acid-based biostimulants (via foliar spray or soil drench) has been shown to boost chlorophyll content, enhance photosynthesis and improve the nutritional status of plants. In fruit trees, this translates into larger fruit size and better quality [36].
- **Microbial Inoculants:** These include beneficial bacteria (e.g. *Azospirillum*, *Bacillus*, *Pseudomonas*, rhizobia) and fungi (mainly arbuscular mycorrhizal fungi, *Trichoderma*, *Beauveria*). Such microbes can fix nitrogen, solubilize soil nutrients (phosphate, potassium) and produce phytohormones [37]. For instance, *Azospirillum* and rhizobia form symbioses with plants to provide nitrogen, reducing the need for synthetic fertilizers. *Bacillus* and *Pseudomonas* species may produce indoleacetic acid (auxin) to stimulate root branching. Mycorrhizal fungi extend the root system into the soil to scavenge water and nutrients, especially phosphorus. All these microbial agents can be applied as seed coatings or soil inoculants. In fruit crops, trials have recorded better root development, earlier flowering and improved fruit set when such beneficial microbes are present [38].
- **Chitosan and Biopolymers:** Chitosan is derived from chitin (found in crustacean shells and fungal cell walls). It acts as a plant defense elicitor, inducing systemic resistance to pests and diseases. It also has biostimulant effects: treated plants often show enhanced growth and nutrient uptake [39]. Other biopolymers such as alginate oligosaccharides (from algae) similarly stimulate plant immunity and yield. For example, spraying chitosan on fruit trees can reduce fungal diseases while also slightly increasing fruit weight and number [40].
- **Silicon:** Soluble silicon (silicic acid) applied to plants can strengthen cell walls by deposition of silica, making tissues more rigid. This has multiple benefits: plants become more drought-tolerant (reduced transpiration), more resistant to pest attack (leaf toughness) and often show better photosynthetic rates under stress [41]. Though not traditionally considered essential for all plants, Si has emerged as an important bio-stimulant in crops like rice and vegetables. Recent research suggests that even in fruit crops like guava or mango, silicon supplementation leads to sturdier plants and higher yields under both normal and adverse conditions [42].
- **Trace Elements and Others:** Small quantities of micronutrients (such as zinc, boron, manganese) are critical for enzyme function and hormone synthesis. Foliar sprays of these elements can correct hidden deficiencies and improve fruit set. Newer bio-stimulants include compounds like triacontanol (a natural plant wax alcohol) which has been shown to enhance growth and yield in limited trials or iodine formulations that, surprisingly, have biostimulant effects beyond their nutritional role [43].

Table 2: Categories of emerging Bio-stimulants and their Effects [44, 45, 46]

Bio-Stimulant Category	Examples (Sources)	Primary Actions on Plants
Seaweed Extracts	Brown algae (*Ascophyllum*, *Ecklonia*)	Contain natural auxins, cytokinins, mannitol, enhance root/shoot growth, stress tolerance, flowering and yield. Promote water uptake and enzyme activation.
Humic/Fulvic Acids	Compost-derived humus, leonardite extracts	Increase soil cation exchange capacity, chelate nutrients, stimulate root proliferation, improve soil moisture retention and nutrient availability.
Protein Hydrolysates (Amino Acids)	Plant/animal protein breakdown products	Supply amino acids, act as osmoprotectants and signal molecules, boost nutrient assimilation, enhance photosynthesis and stress resilience.
Microbial Inoculants	Rhizobium, Azospirillum, Bacillus, Pseudomonas, *Trichoderma*, AM fungi	Fix N_2, solubilize phosphate, produce phytohormones, extend root systems (mycorrhiza), induce systemic resistance. Increase nutrient uptake and disease tolerance.
Chitosan/Biopolymers	Chitin-derived chitosan, alginate oligosaccharides	Elicit plant defense responses, enhance growth and yield, reduce fungal diseases, improve cell wall integrity and water use efficiency.
Silicon (Si)	Potassium silicate, diatomaceous soil components	Deposits silica in tissues, strengthens cell walls, enhances resistance to abiotic (drought) and biotic (pests/diseases) stresses, improves photosynthesis.
Trace Elements	Micronutrients (Zn, B, Mn, Fe)	Act as cofactors for enzymes, improve flowering, fruit setting and quality, rectify latent nutrient deficiencies, modulate hormone activity.
Novel Phytohormones & Compounds	Biostimulant formulations containing gibberellins, melatonin, triacontanol, etc.	Directly regulate development (e.g. fruit set, stem elongation), improve stress signaling, enhance yield attributes.
Combined Formulations	Blends (e.g. seaweed + microbial + amino acids)	Aim to exploit multiple mechanisms (hormonal, nutritional, microbial) simultaneously, often show additive or synergistic effects on plant growth.

Effects on Morphological Traits of Fruit Crops

The application of bio-stimulants often produces noticeable changes in plant morphology the measurable physical aspects of growth. For fruit crops, these changes translate into larger, stronger plants with more potential for fruiting [47]. Typical morphological improvements include:

- **Enhanced Root Development:** Bio-stimulants frequently boost root length, surface area and branching. For instance, seed treatment or soil drenching with humic substances or microbial inoculants often leads to a more extensive root system. Amino acid stimulants can trigger root hair proliferation [48]. A larger root network allows the plant to access water and nutrients more efficiently. In practice, fruit trees treated with these stimulants tend to establish faster in the field and recover better from transplanting or drought [49].
- **Increased Vegetative Growth:** Many biostimulants cause shoots and leaves to grow more vigorously. Treated plants typically exhibit greater plant height, stem thickness and leaf area index than untreated controls [50]. For example, foliar sprays of seaweed extract rich in cytokinins promote leafy growth, while protein hydrolysates enhance overall biomass accumulation. In vines and shrubs (e.g. passionfruit, feijoa), the canopy often becomes bushier, supporting more future fruit load [51].
- **Improved Flowering and Fruit Set:** The number of flowers produced and the success rate of those flowers developing into fruits (fruit set) are crucial for yield. Certain bio-stimulants, notably seaweed extracts and microbial inoculants, have been observed to increase flower bud formation [52]. The natural hormone analogs in these products can mimic gibberellins or auxins, thereby stimulating floral induction. As a result, growers see more flowering clusters and a higher percentage of flowers turning into fruits. For example, in apple orchards and peach groves, pre-bloom applications of seaweed or chitosan have led to heavier flowering and subsequent higher fruit counts [53].
- **Larger Fruit Size and Weight:** Many studies report that fruit size increases following bio-stimulant treatment. This is partly due to enhanced nutrient and water uptake during the fruit development stage. In tomatoes and grapes (often used as models), fruit diameter and average weight can increase by 1020% with certain biostimulants [54]. Similar effects are expected in underutilized fruits: anecdotal reports suggest, for instance, that karonda plants sprayed with seaweed extract bear significantly larger berries and that treated jabuticaba trees produce heavier fruit clusters [55].
- **Overall Yield Improvements:** The culmination of the above changes is reflected in yield per plant or per hectare. In field trials worldwide, crops ranging from citrus to cucumbers have shown yield boosts of 1030% or more when bio-stimulants are used [56]. Table 3 presents specific cases of fruit crops and the observed morphological effects of various biostimulants. Importantly, these results are global and span diverse crops, implying broad applicability. (While some entries are from major fruits, they illustrate principles that apply to many species, including neglected ones.)

Table 3: Selected Fruit Crops, Biostimulant Treatments and Observed Morphological Effects [57, 58, 59, 60]

Fruit Crop	Biostimulant(s) Applied	Morphological/Production Impact	Notes
Banana (*Musa* spp.)	Amino acid hydrolysate + Silicon (SiLife)	Increased plant height and bunch weight, significantly more fruits per bunch, overall yield increased by ~3040%.	Field trials showed treated plants producing ~150 fruits/bunch and yields >110 t/ha (versus controls <80 t/ha).
Apple (*Malus domestica*)	Seaweed extract (Ascophyllum-based)	Higher fruit number per tree, increased fruit size and weight, longer canopy shoots.	Quality also improved: higher vitamin C and phenolic content in apples after seaweed spray.
Peach (*Prunus persica*)	Seaweed extract (dilute foliar sprays)	Greater fruit set and yield, improved coloration (deeper red) of fruit skin, enhanced leaf area.	Seaweed application showed notably redder peaches, indicating better ripening.
Grapevine (*Vitis vinifera*)	Mycorrhizal fungi (Glomus sp.)	More clusters per vine and higher berry weight, stronger root biomass.	Inoculated vines yielded higher grape tonnage and berries with richer color and phenolic compounds.
Strawberry (*Fragaria × ananassa*)	Seaweed + Microbial inoculant combination (dual application)	Thicker crowns, higher foliar biomass, increased fruit number and total yield by ~1520%.	Combined treatments outperformed single biostimulants, berries also had higher sugar content.
Mango (*Mangifera indica*)	Chitosan coating (on fruit/panicle)	Reduced fruit drop, fruits were larger on average, increased shelf-life (less postharvest weight loss).	Chitosan spray induced thicker fruit skins and enhanced ripening uniformity.
Citrus (Orange, *Citrus sinensis*)	Humic acid soil drench	More fruit per tree and slightly larger fruit size, deeper green foliage.	Humic-treated trees showed higher SPAD chlorophyll readings, indicating better nutrition.
Dragonfruit (Pitaya)	Seaweed extract (foliar spray)	Earlier and more abundant flowering, nearly double the fruit yield compared to control.	In trials, treated dragonfruit vines produced more showy flowers and higher number of fruits.
Indian Gooseberry (Amla)	Nitrogen-fixing bacteria (Azospirillum/Rhizobium)	Increased shoot and leaf growth, 2530% higher fruit yield.	Bacterized plants showed higher leaf nitrogen content and larger canopies.
Karonda (*Carissa carandas*)	Seaweed extract (foliar sprays)	Increased berry size (volume) by ~15%, more fruit clusters per plant.	Growers noted visibly plumper fruits after treatment, improving harvest weight.
Passionfruit (*Passiflora edulis*)	Amino acid solution (protein hydrolysate)	Higher vine vigor, greater number of fruits per vine, fruit shell harder (firmer pulp).	Biostimulant-treated vines maintained lush foliage longer, resulting in more mature fruits.
Sapodilla (*Manilkara zapota*)	Mycorrhizal fungi inoculation	Improved seedling establishment, 30% increase in seedling height in nursery.	Inoculated sapodilla seedlings in nursery stage showed significantly more growth.
Jackfruit (*Artocarpus heterophyllus*)	Phosphorus-solubilizing bacteria (Bacillus spp.)	Bigger canopy and higher fruit set, up to 20% increase in total yield.	Treated trees had visibly denser foliage and produced more jackfruits per tree.
Baobab (*Adansonia digitata*)	Humic acid + Mycorrhiza (nursery treatment)	Faster nursery growth, seedlings with longer taproots and healthier leaves.	Seedlings given humic + mycorrhiza established better in trials, promising for field growth.
Orange (*Citrus* spp.)	Zinc and Boron foliar spray	Enhanced flowering and fruit retention, slightly higher citrus yield per hectare.	Corrected common micronutrient deficiencies, improving fruit set in sandy soils.

These examples illustrate that bio-stimulants can markedly alter the morphology of fruit plants. Underlying all these cases is usually the same principle: by enhancing root efficiency and nutrient/hormone balance early on, the plants allocate more resources to growth and reproduction [64]. For instance, early root or seed treatments prime seedlings so that weeks later their stems and leaves are larger. Foliar feeds during vegetative growth boost leaf expansion and stem diameter. During flowering, additives like seaweed hormones or metal micronutrients ensure more blooms mature into fruit. In one banana trial (see Table 3), the combined use of an amino-acid-based drench and a silicon foliar spray nearly doubled yield compared to untreated plants, simply by producing bigger and more numerous bunches. Moreover, these morphological gains tend to compound under stress [65]. A plant with a stronger root system will naturally extract more water during a dry spell, maintaining turgor and photosynthesis when its competitors wilt. Thus, even under identical fertilizer regimes, a bio-stimulant-treated plant can outperform untreated ones by virtue of this extra vigor. This is why growers report that biostimulants not only boost size and number of fruits but also make orchard trees look healthier overall [66].

Effects on Physiological and Biochemical Traits

Alongside visible growth changes, bio-stimulants profoundly affect the inner workings of fruit plants. They can alter physiological processes (like photosynthesis and water use) and biochemical traits (such as nutrient composition and antioxidant levels). These changes are often measured as improved efficiency or resilience of plant functions [67]. Key impacts include:

- **Enhanced Photosynthetic Capacity:** Many bio-stimulants increase leaf chlorophyll content and the activity of photosynthetic enzymes. For instance, foliar applications of seaweed or amino acid extracts have been shown to raise leaf chlorophyll by 1020%, which directly boosts photosynthesis rates. A greener, more efficient leaf means more sugars are produced to fuel fruit development. Treated plants often display higher Fv/Fm ratios (a measure of photochemical efficiency) under stress conditions, indicating healthier chloroplasts [68].
- **Improved Nutrient Uptake and Assimilation:** By stimulating root growth and modifying root membrane transporters, biostimulants enable plants to absorb soil nutrients more effectively. Microbial inoculants can make previously unavailable nutrients accessible (e.g. converting fixed nitrogen or mineral phosphorus). Humic acids chelate micronutrients like iron and zinc, preventing them from precipitating [69]. As a result, levels of key nutrients in leaves and fruits often rise. In fruit crops, this might mean higher nitrogen and potassium in the tissues, leading to larger fruits with higher sugar content. Additionally, some biostimulants stimulate activity of nitrogen-metabolizing enzymes, so the plant uses fertilizer more efficiently [70].
- **Hormonal and Growth Regulator Effects:** Since many bio-stimulants contain or induce plant hormones, they directly affect developmental pathways. Seaweed extracts, for example, have natural auxins and cytokinins which accelerate cell division and expansion. Amino acids can be precursors to hormones (e.g. phenylalanine to salicylic acid). Such hormonal modulation can advance fruit maturation or enhance cell expansion in developing fruits. It also often triggers systemic responses for instance, chitosan can induce jasmonic acid pathways, priming plants for defense. These hormone-like effects mean a biostimulant might shorten the time to flowering or ripening, helping farmers achieve earlier harvests or more uniform fruit quality [71].
- **Stress Physiology and Osmotic Balance:** Under environmental stress (drought, salinity, heat), plants naturally accumulate osmoprotectants like proline and soluble sugars. Biostimulants can enhance this adaptive response. Amino acids, notably proline itself or precursors accumulate faster in treated plants, which stabilize proteins and membranes under water deficit [72]. Silicon deposition in tissues also reduces non-stomatal water loss. Moreover, many biostimulants up-regulate antioxidant enzymes (catalase, superoxide dismutase) and secondary metabolites. For example, treated fruits and leaves often show higher levels of phenolic compounds, flavonoids and vitamin C. In one apricot study, a seaweed+yeast biostimulant doubled the polyphenol content in the fruit skin. Such biochemical boosts not only improve plant health but also increase the nutritional and shelf-life qualities of the fruit [73].
- **Improved Postharvest Quality:** Some physiological effects of bio-stimulants carry over into harvested fruit. Fruits from treated trees may have firmer texture, higher soluble solids (Brix), or elevated antioxidant levels. Chitosan coatings on fruit (as a postharvest biostimulant) can reduce respiration rates, delaying ripening and weight loss. Enhanced nutrient and sugar accumulation in fruits translates to better taste and storage potential. For instance, tomatoes grown with protein hydrolysate sprays often taste sweeter and have more lycopene. Although specific data on underutilized fruits is sparse, it stands to reason that similar benefits occur [74].

The overall physiological picture is one of greater efficiency and resilience. A plant with stimulated physiology can do more with the same inputs and survive harsher conditions. In managed horticulture, this means less fertilizer may be needed and plants maintain yield under off-season or suboptimal weather. Critically, many of these effects such as increased antioxidants also add value for the consumer, linking agricultural productivity with food quality [75].

Table 4: Plant Morphological and Physiological Parameters Influenced by Bio-Stimulants [76, 77, 78]

Plant Parameter	Typical Effect of Bio-Stimulant	Implication for Fruit Crops
Root Length and Biomass	Increased lateral root and hair development, greater total root volume.	Improves water/nutrient absorption, leading to sturdier plants.
Shoot Height and Stem Girth	Increased elongation and thicker stems.	Supports larger fruit loads, plants can grow into tree size faster.
Leaf Area and Leaf Number	More and larger leaves, higher leaf area index.	Higher photosynthetic surface area, more energy for fruit growth.
Leaf Chlorophyll Content	Elevated chlorophyll concentration per leaf, darker green foliage.	Higher photosynthetic capacity and efficiency.
Photosynthetic Rate (Pn)	Increased net CO_2 assimilation, better stomatal conductance.	Greater production of sugars and biomass for fruit filling.
Flower Count per Plant	Increased number of flower buds or clusters.	Potentially more fruits per plant (if pollination succeeds).
Fruit Set (% of flowers fruited)	Higher proportion of flowers maturing into fruits.	Boosts effective yield, reduces fruit drop.
Fruit Weight/Size	Larger individual fruit dimensions (diameter, weight).	Each fruit contains more flesh/nutrients, overall yield rises.
Total Fruit Yield	Increase in kg of fruit per plant or area (often +1030%).	Direct improvement in farm productivity and profitability.
Fruit Brix (sugars)	Often higher soluble solids (sweetness) due to better nutrient supply.	Improved taste and processing quality.
Vitamin/Chemical Content	Elevated vitamins (C, E, etc.) and antioxidants (flavonoids).	Fruit has higher nutritional value and possibly longer shelf life.
Stress Tolerance (drought/salinity)	Enhanced osmoprotectant levels (proline, sugars), better water use efficiency.	Plants maintain growth and yield under stress that would limit others.
Leaf/Stem Water Content	Improved water retention in tissues.	Delays wilting support sustained metabolic activity in dry periods.
Enzyme Activity (N metabolism, etc.)	Higher activity of nitrate reductase, peroxidase, etc.	Nutrients are assimilated more effectively, supporting growth.
Phytohormone Balance	Modulation of auxin, cytokinin, gibberellin levels (often elevated).	Regulates growth and development phases (budding, flowering, expansion).
Antioxidant Enzyme Levels	Increased catalase, SOD, etc.	Protects cells from oxidative damage, especially under stress.

Together, these morphological and physiological improvements create a synergistic effect on plant performance. A fruit tree that is taller, bushier and has more leaves (morphological gains) will naturally photosynthesize more, especially if those leaves are richer in chlorophyll and enzymes (physiological gains). Bio-stimulants help achieve both sets of benefits simultaneously [79].

Applications in Underutilized Fruit Cultivation

- Translating these general effects to underutilized fruits requires field trials and experiments, which are increasingly being conducted worldwide. Although the body of published research is still smaller than for major crops, several case studies illustrate the promise. For example, in India, foliar spraying of seaweed extract on *Emblica officinalis* (amla) trees resulted in more flower clusters and a 20% higher fruit yield compared to untreated trees. The treated trees also showed higher leaf nitrogen and potassium content, reflecting improved nutrition. In Southeast Asia, greenhouse trials with dragonfruit seedlings treated with humic acid or beneficial bacteria reported stronger root growth and earlier flowering. African agroforestry researchers have noted that baobab seedlings inoculated with mycorrhizal fungi establish faster and survive dry periods better than controls [80].
- Another notable trial involved jaboticaba (*Plinia cauliflora*), a Brazilian fruit tree, where soil application of a microbial biofertilizer containing *Bacillus* and *Trichoderma* strains significantly increased fruit weight and sugar content. In Costa Rica, small-scale farmers tested seaweed extract on passionfruit vines and observed a marked increase in fruit size and oil content of the seeds. In the case of mangosteen (a Southeast Asian tropical fruit), applications of amino-acid biostimulants in nursery stage accelerated vegetative growth, enabling earlier flowering in the orchard [81].
- Sometimes, commercial products specially formulated for fruit crops have been used. A Mediterranean study showed that a yeast extract-based biostimulant applied to table grape vines improved berry firmness and anthocyanin levels, important for color and quality. In China, citrus growers have begun using potassium humate drench treatments to push fruit ripening forward and prevent premature drop. Even container-grown kiwifruit (an exotic but commercially minor fruit in many countries) responded to chitosan foliar sprays with thicker stems and delayed leaf senescence, indicating stronger health as the plant entered winter [82].
- While controlled studies are ongoing, farmers also experiment. Many report that mixing biostimulants with irrigation water or foliar misting once a month leads to noticeably lusher growth and better yields in their tropical orchard crops like papaya, lychee and more uncommon fruits like passion fruit (maracuja) and salak (snake fruit). Such empirical evidence, though anecdotal, complements the scientific findings [83].
- Importantly, most of the physiological processes stimulated by biostimulants are universal across plant species. Thus, even if underutilized fruits have had less formal research, it is reasonable to infer similar outcomes. For instance, a boost in nutrient uptake or stress enzyme levels should help any fruit tree. Indeed,

developmental and stress biology is broadly conserved among plants. Therefore, the agricultural community anticipates that biostimulant application can help unlock the productivity of under-researched fruit trees in the same way it aids major crops [84].

Global Perspectives and Future Outlook

- The use of bio-stimulants in horticulture has expanded rapidly on all continents. In Europe, regulatory frameworks now officially recognize biostimulants as a product category, leading many vineyard and orchard operations to adopt them as part of integrated plant nutrition plans. Farmers in the United States and Canada use organic extracts and microbial inoculants to enhance fruit and nut crops, driven by organic market premiums [85]. In Asia (notably China, India and Southeast Asia), where underutilized fruits are native, there is growing interest from both government research and private companies in developing biostimulant technologies tailored to local specialty fruits. Africa and Latin America, home to countless indigenous fruits, are also ramping up trials, often in collaboration with international agricultural organizations. For example, a multi-country project in arid Africa is testing combined seaweed and biochar treatments on local fruit trees to improve food security [86].
- The global biostimulant market reflects this trend, with an estimated compound annual growth rate exceeding 10%. Key drivers include concerns over fertilizer overuse, climate change adaptation and consumer demand for healthier produce. Biostimulants align with sustainable development goals by potentially reducing inputs, enhancing nutrition and making marginal lands more productive. In this context, underutilized fruits represent a major opportunity [87]. By applying biostimulants, farmers could make these crops commercially viable, tapping into new markets for superfoods and organic products. Indeed, some underutilized fruits have already attracted niche markets (acai, goji berries, baobab powder). Improved cultivation techniques including biostimulant use could transition such fruits from novelty items to mainstream commodities [88].
- Challenges remain. Many biostimulant products vary in composition due to natural sourcing, so standardizing quality is an ongoing effort. Specific application protocols (timing, dosage, combinations) need optimization for each crop and environment. Moreover, adoption in regions with underutilized fruits requires extension services to educate smallholders [89]. Nonetheless, early adoption examples are promising. In Australia, growers of the wild Kakadu plum now routinely use seaweed sprays to increase yields. In India, women-led cooperatives for gooseberry processing are advising farmers on microbial inoculants to boost berry harvests. International exchange of such knowledge is accelerating through conferences and journals focused on neglected crops [90].
- Looking forward, research is likely to deepen our understanding of how bio-stimulants can be fine-tuned. Advances in genomics and metabolomics are revealing plantmicrobe interactions at the molecular level, enabling development of targeted bio-stimulant strains. Climate-smart strategies are exploring which stimulants work best under heat or drought [91]. There is also interest in circular economy approaches for example, using extracts from invasive seaweed species or agricultural waste as low-cost biostimulants. For underutilized fruits, breeding programs combined with bio-stimulant regimes may rapidly improve yields. The prospect of synchronizing flowering and increasing fruit uniformity (as shown with products like seaweed/yeast mixes) could make many local fruits suitable for export markets [92].

Conclusion

Emerging bio-stimulants offer a powerful set of tools to enhance the morpho-physiological performance of underutilized fruit crops around the globe. As this review highlights, substances derived from seaweed, humus, protein, chitin, silicon and beneficial microbes can invigorate plant growth from root to shoot, boost photosynthesis and nutrient use and amplify reproductive success. In practical terms, farmers see taller, leafier fruit trees that flower more profusely, bear more and larger fruits and withstand stresses better. Biochemical changes higher vitamins, antioxidants and enzymes in the plant further underpin these gains. These effects have been well-documented in major horticultural crops and increasingly observed in minor fruits as well. Early case studies on species like dragonfruit, amla and baobab indicate that the advantages of biostimulants translate to previously neglected trees. Given the climate resilience and nutritional richness of underutilized fruits, applying bio-stimulant technology could substantially improve global food diversity and security. Bio-stimulants can help overcome the agronomic limitations that have kept these crops marginal. While more research is needed to fine-tune dosages and combinations for each species and region, the overarching conclusion is clear: bio-stimulants represent an eco-friendly innovation to raise the productivity of a broad spectrum of fruit crops. They align with sustainable agriculture by reducing chemical inputs and enhancing natural plant processes. As regulatory and market conditions evolve, it is likely that the integration of bio-stimulants into cultivation practices for underutilized fruits will only grow. Ultimately, leveraging these biological enhancers may make it feasible to bring many traditional fruit species into mainstream cultivation, benefiting growers and consumers worldwide through more nutritious harvests and diversified agriculture.

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