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Advances in biostimulants as an integrated pest management tool in horticulture

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1 Introduction

Plant biostimulants are microorganisms, microbial derivatives, and materials of mineral, marine, or botanical origin that stimulate plant physiological responses including induced systemic resistance (ISR), and improve nutrient or water uptake, promote plant growth and health, or impart tolerance to biotic and abiotic stressors, without having nutritional or pesticidal properties. This definition covers both the technical and the regulatory aspects of biostimulants. However, there are some exceptions to the biostimulant products that are available in the market, due to the inherent nutritional or pesticidal properties of some of the active ingredients or their sources. For example, silicon has biostimulant properties, but when applied as calcium or potassium silicate,

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plants receive calcium and potassium as additional nutrients along with silicon (Savvas and Ntatsi, 2015). Some protein hydrolysates have several nutrient components in addition to biostimulant activity (Baglieri et al., 2014; Visconi et al., 2015). Similarly, certain microorganisms have both biostimulatory and biopesticidal properties and depending on the strain or application procedure, they are registered or used for one of these purposes (Kim et al., 2017; Fiorentino et al., 2018; Dara, 2019a). Crop habitat is a dynamic environment with complex interactions among various biotic and abiotic elements. Sometimes, biostimulatory and biopesticidal properties overlap, interchange, or are activated or synergized by their interactions with other influencing factors. To avoid under-exploring the full potential of biostimulants, this chapter does not involve the regulatory aspects but focuses only on the biostimulatory properties of various active ingredients and how they can be used in integrated pest management (IPM) programs as a part of cultural control. The IPM section briefly describes the new IPM model (Dara, 2019b), the role of biostimulants in improving crop production and protection, and lists various categories of biostimulants. The following sections focus on the role of biostimulants in enhancing crop growth, health, and yield, improving soil health, inducing natural resistance, suppressing diseases and arthropod pests, and imparting tolerance to abiotic stresses. Various interactions of biostimulants with other biotic and abiotic factors in the crop environment, the different strategies for successfully using biostimulants in food production, and the challenges and future needs in promoting the use of biostimulants will be discussed in the concluding sections.

2 Integrated pest management

The traditional definition of IPM was limited to pest monitoring, various control options, and making treatment decisions based on economic thresholds with a focus on protecting the ecosystem (Peterson et al., 2018). In many cases, the rotational use of pesticides with different modes of action, mainly intended for managing pesticide resistance, is considered as practicing IPM. In general, a heavy emphasis on minimizing pesticide applications with a focus on environmental safety, a lack of consideration for factors that influence pest management practices at the farm level, and various other reasons have limited the widescale implementation of IPM strategies. The transformation of agriculture as a global enterprise, the technological advances in multiple disciplines of crop production, the growing world populations and their food needs, and an increasing demand for sustainably produced food warranted a practical IPM model that is economically viable, environmentally sustainable, and socially acceptable. As a result, the new IPM model has been developed to meet the needs of modern-day agriculture (Dara, 2019b). The new model provides

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a template for an integrated crop production system that makes the best use of traditional and modern technologies, incorporates information management and effective decision-making, and emphasizes the importance of research and outreach to maintain farm profitability and food affordability (Fig. 1). The knowledge of pests, the vulnerable stages of their life cycle, and the influence of various agronomic practices on pest populations and their damage are critical in the new IPM model as they help devise and implement effective strategies. Good agronomic practices such as using biostimulants not only improve crop health but also lessen the burden on crop protection directly or indirectly. Biostimulants help crop production in one or more of the following ways (Fig. 2):

1 Stimulate ISR and prime the plants for biotic and abiotic stressors.
2 Improve water and nutrient use efficiency and thus reduce the input costs and associated environmental risks from leaching or runoff,

Figure 1 The new integrated pest management (IPM) model provides a template for various crop and pest situations to produce crops in an economically viable, socially acceptable, and environmentally sustainable manner (Dara, 2019b).

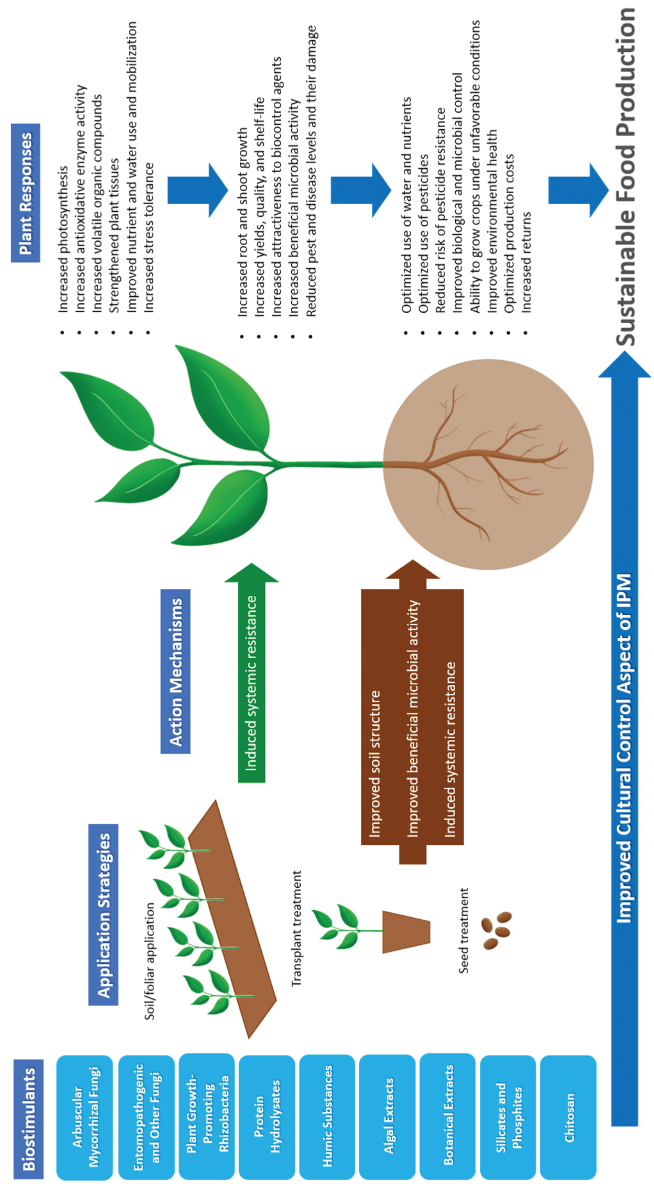

Figure 2 Biostimulant categories, application strategies, mechanisms of action, and their impact on crop production and protection.

enhance plant vigor and yields and thus compensate for losses due to pest damage.

3 Help optimize fertilizer inputs and prevent overuse of certain nutrients that increase a plant's attractiveness to pests.
4 Strengthen plant tissues and reduce pest damage or proliferation.
5 Release metabolites or enhance the production of plant defense chemicals that negatively influence pest populations or attract natural enemies.
6 Contribute to the reduction of pest management practices, pesticide resistance, and the potential negative impact on the environment.
7 Build soil structure and promote natural beneficial microbial populations that further improve crop health in the short term and improve soil health in the long term.
8 Contribute to carbon sequestration and a reduction in the use of synthetic agricultural inputs.

One key area of IPM is focusing on preventive measures and minimizing the reliance on curative measures. Biostimulants are good agronomic inputs that contribute to these preventive measures as a part of cultural control. Biostimulant use has increased in recent years as a result of increased market availability, research and outreach efforts, the need for improved crop production practices, and the interest in sustainably produced food items. Examples of some research studies with commercially available or developmental products that have demonstrated the benefits of various categories of biostimulants, including arbuscular mycorrhizal fungi (AMF), entomopathogenic and other fungi, plant growth-promoting rhizobacteria (PGPR), protein hydrolysates, humic substances, algal and botanical extracts, and minerals are discussed in the following sections.

3 Enhancement of crop growth, health and yield

Biostimulants are primarily used for improving crop growth, health, and yields through one or more mechanisms. Increased nutrient and water uptake through enhanced root growth, increased solubility or bioavailability of nutrients, higher beneficial microbial activity, and improved metabolic activity are among various mechanisms that aid plant growth and health.

3.1 Arbuscular mycorrhizal fungi (AMF)

AMF have been used in crop production for a long time for their biostimulatory properties. *Glomus aggregatum* significantly enhanced the growth of grape rootstocks with improved root morphology (Aguín et al., 2004). Inoculation of *Glomus mosseae* resulted in higher biomass and concentration of some nutrients in shoots, and higher single-fruit weight in cucumbers (Wang et al., 2008). *Glomus versiforme* inoculation improved osmotic adjustment, leaf water potential, and soluble sugar content, and increased the transpiration and photosynthetic rates among other changes, resulting in improved plant growth of tangerine (Wu and Xia, 2006). A review by Rouphael et al. (2015) discussed yield and growth improvement of several horticultural crops growing under nutrient-deficient conditions with the help of AMF.

3.2 Entomopathogenic and other fungi

Although not primarily used as biostimulants, entomopathogenic fungi such as *Beauveria bassiana*, *Cordyceps fumosorosea*, and *Metarhizium* spp. appear to have biostimulatory properties such as promoting plant growth through improved nutrient and water uptake and alleviating plant stresses. A strain of *Beauveria bassiana* is currently available in the United States as a soil amendment, for its biostimulant properties. A recent review of entomopathogenic fungi described various non-entomopathogenic roles and how they can be exploited as holistic tools (Dara, 2019a). When entomopathogenic fungi are applied for arthropod pest control, they also benefit plants through their endophytic and mycorrhiza-like roles and improve plant growth and health. Additionally, entomopathogenic fungi could also serve as the substitutes of AMF for crops that have a poor relationship with AMF.

The mycoparasitic fungal species of *Trichoderma* are commonly used as biofungicides, but some of them also have biostimulatory properties and are sold as biofertilizers. A biofertilizer enriched with *Trichoderma harzianum* significantly increased tomato yields, quality, and nutritional value and contributed to the reduction of synthetic fertilizers (Molla et al., 2012). A biofungicidal strain of *T. harzianum* increased the access of AMF to non-host brassica plants and prompted plant growth (Poveda et al., 2019). A *Trichoderma*-based biofertilizer enhanced the soil enzyme activity that improved nutrient availability and promoted the growth, quality, and yield of flowering Chinese cabbage (Ji et al., 2020). Similarly, positive results were seen in yield or other parameters from field studies conducted in California strawberries with biostimulants that have *T. harzianum* and *T. virens* or *T. harzianum* and *Bacillus amyloliquefaciens* (Dara, 2020, 2021), and a tomato study with a combination of products where one of them contained *T. harzianum* and some PGPR (Dara and Lewis, 2019).

3.3 Plant growth-promoting rhizobacteria (PGPR)

The rhizosphere environment supports an abundance of microorganisms due to the presence of organic matter, root exudates, nutrients, and moisture.

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Among these microorganisms are the PGPR, which regulate plant hormones, produce antibiotics and organic compounds, fix nitrogen, solubilize phosphate, improve soil structure, increase nutrient and water uptake, and alleviate plant stresses (Glick, 2012; Backer et al., 2018). Similarly, root exudates also influence soil microbial communities (Bakker et al., 2012). Thus, both plants and soil microorganisms influence and depend on each other. Examples of PGPR genera that are commonly used in crop production include *Agrobacterium*, *Azospirillum*, *Azotobacter*, *Bacillus*, *Burkholderia*, *Delfitia*, *Paenibacillus*, *Pseudomonas*, *Rhizobium*, *Serratia*, and *Streptomyces* that enhanced plant growth and yields in multiple studies. For example, *Azospirillum brasilense* improved root and shoot growth in strawberry (Pedraza et al., 2010), *Bacillus subtilis* increased shoot development and yields in apricot (Esitken et al., 2002), *Pseudomonas fluorescens* improved nutrient uptake and promoted plant growth and yields in broccoli (Tanwar et al., 2014), a consortium of *Pseudomonas putida*, *Camanomonas testosterone*, *Citrobacter freundii*, and *Enterobacter cloacae* and a nutrient program with a product containing *Azotobacter chroococcum*, *B. subtilis*, *Bacillus megaterium*, *Bacillus mycoides*, and *T. harzianaum* improved tomato yields (Dara and Lewis, 2019).

3.4 Protein hydrolystates

Protein hydrolysates contain peptides and amino acids derived from enzymatic or chemical hydrolysis of animal- or plant-derived materials and have biostimulant effects that help plants in multiple ways (Colla et al., 2015). Significant improvement in marketable strawberry yields was seen when a hydrolysate of grocery store food waste was used as a substitute for the grower-standard nutrient program at 50% or 100% through drip application in a commercial field in California (Dara, 2017). An Italian study showed that protein hydrolysates improved the biomass of the aerial parts and fruit diameter, both under well-watered and water-stressed conditions (Meggio et al., 2020). In another Italian study, a protein hydrolysate derived from legume seeds increased antioxidant activities, total soluble solids, mineral and nutritional value, photosynthetic activity, and yields of tomato (Rouphael et al., 2017). Such a positive impact on tomato yields and quality parameters was also seen in another study from a legume-based protein hydrolysate, seaweed extract, and a tropical plant extract (Colla et al., 2017). Similarly, a soy protein hydrolysate improved strawberry fruit yields comparable to synthetic fertilizers in a Californian study (Dara, 2020).

3.5 Humic substances

Another group of biostimulants comprises humic substances, which are biologically derived organic matter in soil and water that regulate critical ecological and environmental processes and have a major impact on plant growth and metabolism (Nardi et al., 2002; Canellas et al., 2015). Reducing soil compaction, increasing nutrient use efficiency and microbial activity, and improving plant biomass are some of the benefits of humic substances with their hormone (auxin)-like activity (Nardi et al., 2002; Rose et al., 2014). In a Cuban study, humates from vermicompost decreased total carbohydrate content, increased protein content, nitrate uptake, and crop yields, and shorted the crop cycle by 21 days in lettuce (Hernandez et al., 2015). In a potted plant study in Italy, humic-like substances derived from alkaline hydrolysis of tomato plant residue increased the nitrogen assimilation in kidney bean (Baglieri et al., 2014). A meta-analysis by Rose et al. (2014) showed that exogenously applied humic substances increased the root biomass by 21% and the shoot biomass by 22%. Similarly, Seyedbagheri (2010) reported from 17 years of research studies in Idaho, USA, that a 11–20% yield increase was seen in potato from various humic acid products. An extensive review by Canellas et al. (2015) summarized the positive effects of humic substances in several horticultural crops including fruits such as apricots, grapes, pineapple, and strawberry, and vegetables such as broccoli, beans, eggplant, garlic, lettuce, onion, pepper, potato, and tomato with an increase in root dry weight by up to 124% and increase in yield by 80% in some of these crops.

3.6 Algal extracts

Extracts from several species of micro- and macroalgae have been used in crop production. Species of *Aphanizomenon*, *Chlorella*, *Dunaliella*, and *Spirulina* are among the microalgae used for their biostimulant and biofertilizer properties. Species of *Ascophyllum*, *Durvillea*, *Ecklonia*, *Saragassum* (brown algae), *Ulva* (green algae), and *Gelidium* (red algae) are some of the common macroalgae or seaweeds used for improving plant growth or relieving them from stresses. A bioassay conducted in Brazil by immersing onion seedlings in a combination of the microalga *Scendesmus subspicatus* and humic acid showed synergism and promoted plant growth and improved bulb caliber, sugar and protein content, and yields (Gemin et al., 2019). An Indian study showed faster germination and plant growth, and improved root and shoot development of tomato from seed treatment; and higher chlorophyll content, and increased root and shoot development from foliar application of a microalgal consortium (Supraja et al., 2020). In an Italian study, Barone et al. (2018) showed that extracts of the microalgae *Chlorella vulgaris* and *Scenedesmus quadricauda* upregulated several genes of sugar beets putatively involved in sulfate starvation, and triggered primary and secondary metabolic pathways and intracellular transport, resulting in improved root development and nutrient uptake. Similarly, treating tomato and pepper plants with the polysaccharide extract of *Spirulina platensis* resulted in as much as a 30% increase in plant size, 230% increase in root weight, and 100% increase in size and number of nodes, in a Moroccan study (Elarroussi et al., 2016). Microalgae also have various plant hormones such as auxins, cytokinins, and gibberellins and influence several physiological processes related to plant growth, development, maturity, yields, and abiotic stress tolerance (Ronga et al., 2019).

Several macroalgal biostimulants are available around the world, and the majority are based on *Ascophyllum nodosum* (Sharma et al., 2014). Improved plant growth, chlorophyll content, nutritional value, yield, or other benefits were seen from macroalgal biostimulants in apple (Spinelli et al., 2009), onion (Araujo et al., 2012), orange (Fornes et al., 2002), peanut (Featonby-Smith and van Staden, 1987), strawberry (Dara and Peck, 2018), and various other crops. A review by Battacharyya et al. (2015) summarized the benefits of macroalgal extracts in several fruit and vegetable crops, with increased germination, plant growth, chlorophyll content, fruit yield and quality, nutritional value, and early maturity among the several parameters measured.

3.7 Botanical extracts

Several botanical extracts are commonly used as biopesticides, and some of them have biostimulatory properties. Field studies conducted in California in strawberry and tomato with cold-pressed neem extract containing neem oil and azadirachtin, carboxylic acids from rice hulls, and extracts of black walnut and willow showed yield improvements (Dara and Peck, 2018; Dara, 2019c; Dara, 2021). Godlewska et al. (2019) evaluated raw extracts of dandelion, mugwort, and other plants applied to white head cabbage and observed an increase of shoot and root growth by 246% and 106%, respectively. Ali et al. (2019) reported that a single foliar pre-transplant application of garlic bulb extract improved plant growth and antioxidant activity of eggplant.

3.8 Silicates and phosphites

In addition to macronutrients and micronutrients that ensure optimal plant growth and health, products based on silicon and phosphorus have biostimulatory effects of improving mechanical strength, modifying leaf architecture for improved exposure to sunlight, enhancing the activity of antioxidative enzymes to reduce oxidative damage, and improving water use efficiency, mineral uptake, and photosynthesis, among others (Gómez-Merino and Trejo-Téllez, 2015; Savvas and Ntatsi, 2015). Several studies have demonstrated the benefits of using silica-based products in improving plant growth or yields. For example, the application of silica clay improved the fresh weight of onion leaves by 46% (Araujo et al., 2012). Potassium silicate application resulted in a numerical increase of tomato yields by 27% (Dara and Lewis, 2019). Substrate application of potassium silicate and foliar application of sodium silicate improved plant and flower characters of gerbera (Kamenidou et al., 2010). A combination of silicon- and seaweed-based products improved strawberry yields by 16% (Dara and Peck, 2018). Similarly, phosphite improved the yield parameters in celery, lettuce, onion, pepper, potato, strawberry, and tomato when applied as phosphorous acid (Rickard, 2000; Bertsch et al., 2009; Estrada-Ortiz et al., 2012) and emergence, early growth, and mycorrhizal colonization in potato seed tubers and root and shoot growth in strawberry when applied as potassium phosphite (Glinicki et al., 2010; Tambascio et al., 2014).

3.9 Chitosan

Chitosan is a polysaccharide derived from chitin in the exoskeleton of shellfish. It is also present in the arthropod exoskeleton and in fungi. Similar to other biostimulants, chitosan also induces plant defenses and imparts tolerance to various stresses. A review by Pichyangkura and Chadchawan (2015) discussed increased antioxidant activity in apricot, lychee, grapes, navel oranges, sweet basil, and tomato, and improved growth parameters in artichoke, chilli pepper, Indian spinach, okra, watermelon, and several ornamental crops, with chitosan application.

4 Enhancement of soil health

Soil is more than dirt and is full of life. Organic matter and microbial communities are the major components of soil, which influence its water holding capacity and nutrient content. Soils rich in organic matter and beneficial microorganisms improve the physical, chemical, and biological properties of soil, which in turn influence plant growth and health. Healthy soils are also important for nutrient cycling and water conservation. Most biostimulant materials enrich soils with organic molecules, beneficial microorganisms, or minerals. For example, humic substances, being a major component of soil organic matter, have a major impact on soil structure, microbial activity, and overall soil health. Humic substances also influence heavy metal mobilization in soil with improved leachability or plant uptake (Shahid et al., 2012; Canellas et al., 2015). Certain microorganisms such as *B. subtilis* can also be used for the bioremediation of soils (Nadhirawaty and Titah, 2019). Microalgae can remove antibiotics, pharmaceuticals, and personal care products from water and such benefits can be extended for improving soil health as well (Xiong et al., 2017; Kiki et al., 2019; Hena et al., 2021). AMF, PGPR, and other biostimulants fix, mobilize, solubilize, or increase the bioavailability of nutrients in soils and thus improve

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soil health (Pindi and Satyanarayana, 2012; De Pascale et al., 2017). Soil health and soilborne disease incidence are closely related, and improved soil health through organic and microbial amendments and other cultural practices is important for disease suppression (Janvier et al., 2007). Similarly, improved soil quality and health through organic amendments and other practices not only improves water and nutrient availability, but also increases the resilience of soil against adverse environmental conditions and contributes to disease suppression (Lal, 2016).

5 Inducing natural resistance

Plants respond to various beneficial and harmful stimulants of both a biotic and an abiotic nature and trigger defense mechanisms to naturally induce resistance to stresses. The mechanism where the salicylic acid pathway is activated in response to virulent and avirulent pathogens, nonpathogenic microorganisms, chemicals, and other stressors is called systemic acquired resistance (SAR) (Dara, 2021). The mechanism where jasmonic acid and ethylene pathways are activated in response to beneficial microorganisms is called ISR. Pathogenesis-related proteins produced in both mechanisms also help plants perform well under stress. While SAR is more of a curative or reactive strategy, ISR is a proactive strategy. Many biostimulants activate ISR and prime plants for potential stressors. Several studies have demonstrated induced resistance from biostimulants including algal extracts (Raghavendra et al., 2007; Sharma et al., 2014), AMF (Jung et al., 2012; Cameron et al., 2013), *Trichoderma* (Yoshioka et al., 2012), PGPR (Zehnder et al., 2001), protein hydrolysates and humic substances (Nardi et al., 2016), and chitosan (Nandeeshkumar et al., 2008). Primed plants have enhanced responses to stressors and thus mitigate their negative impact (Pastor et al., 2014). Although some biostimulatory active ingredients may also exhibit pesticidal properties, ISR is the primary mechanism in crop protection and in their role in IPM.

6 Suppression of diseases

6.1 Arbuscular mycorrhizal fungi and other microorganisms

Numerous studies have demonstrated the role of biostimulants in disease suppression through ISR and other mechanisms. Larkin (2008) reported that an AMF inoculant containing six *Glomus* spp., *Gigospora margarita*, and *Paraglomus brazianum* reduced stem canker and black scurf caused by *Rhizoctonia solani* in potato by 17–28%. Larkin (2008) also found that when aerobically composted tea was used alone and in combination with a mixture of six *Bacillus* spp., *Streptomyces griseoviridis*, *T. harzianum*, humic acids, and

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seaweed and yeast extracts in a crop rotation with barley/ryegrass, the incidence of stem canker and black scurf, and the common scab caused by *Streptomyces scabiei* declined by 18–33%, with a 20–23% yield increase. In another study, the *T. harzianum* strain T39 reduced symptoms of downy mildew caused by *Plasmopara viticola* by triggering resistance locally and systemically (Perazzolli et al., 2008), similar to that seen in resistant genotypes (Perazzolli et al., 2012). Similarly, a strain of *T. harzianum*, in the presence of root rot-causing *Fusarium solani*, upregulated several genes involved in plant defenses in olive (Amira et al., 2017).

6.2 Plant growth-promoting rhizobacteria

Wei et al. (2011) demonstrated that fortifying an organic fertilizer with two strains of *B. amyloliquefaciens* reduced the incidence of tomato wilt caused by *Ralstonia solanacearum* in greenhouse and field studies. Omara et al. (2017) reported that treating soybean seedlings with PGPR *Methylobacterium aminovorans* and *M. rhodinum*, *Bradyrhizobium japonicum*, *B. megaterium* var. *phosphaticum*, and the mycoparasitic fungus *Trichoderma viride* suppressed damping off caused by *R. solani*. These treatments also increased the nodule numbers; dry weight of nodules; nitrogen, phosphorus, and potassium content; and seed yield. Recep et al. (2009) observed that 17 strains of *B. amyloliquefaciens*, *Bacillus atrophaeus*, *Bacillus pumilus*, *Bacillus macerans*, *Burkholderia cepacia*, *Flavobacter balastinium*, and *Pseudomonas putida* inhibited some of the dry rot-causing *Fusarium oxysporum*, *Fusarium culmorum*, and *Fusarium sambucinum, in vitro*. However, only the OSU-7 strain of *B. cepacia* controlled the disease under storage conditions. Other studies demonstrated similar disease suppression including the control of shot-hole disease (*Coryneum blight*) in apricot with *B. subtilis* (Esitken et al., 2002), tomato yellow leaf curl virus with *Enterobacter asburiae* (Li et al., 2016), *F. oxysporum* and *Fusarium guttiforme* with chitinase from *Chromobacterium violaceum* (Sousa et al., 2019), and *Verticillium dahliae* with cyclodextrin glycosyltransferase, an antimicrobial protein, from *Bacillus cereus* YUPP-10 (Zhou et al., 2021).

6.3 Protein hydrolysates

Soybean and casein hydrolysates reduced downy mildew infection in grape by 76% and 63%, respectively (Lachhab et al., 2014). Both hydrolysates boosted the plant defenses by upregulating the genes responsible for pathogenesis-related proteins and the stilbene synthase enzyme involved in the production of resveratrol, a defensive phytoalexin. In another study, guar hydrolysate suppressed *Pdosphaera xanthii*, the causal agent of powdery mildew, in zucchini (Cappelletti et al., 2017).

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6.4 Humic substances

Disease suppression is one of the benefits of humic substances in addition to their impact on improving crop health and yields. Hernandez et al. (2015) observed reduced disease incidence in lettuce when vermicompost was applied. Increased phenylalanine ammonia lyase activity, which improves plant defenses, was thought to be responsible for disease suppression. Suppression of *Pythium* damping off in cucumber, *Rhizoctonia* root rot in radish, and *Verticillum* wilt in strawberry were observed from vermicompost application (Chaoui et al., 2002). Similarly, the combination of vermicompost and wood vinegar (pyroligneous acid) reduced *V. dahliae* in cucumber (Saberi et al., 2013). Several other studies demonstrated the impact of humic substances in improving crop health through disease suppression (Olivares et al., 2017; Jindo et al., 2020)

6.5 Algal and botanical extracts

A review by Shukla et al. (2021) explained the role of seaweed extracts in priming plants and triggering defense mechanisms against plant pathogens. Seaweed polysaccharides and their derivate oligosaccharides activate the salicylic, the jasmonic acid, and the ethylene signaling pathways that increase the production of pathogenesis-related proteins and other compounds with antimicrobial activity, and offer protection from pathogens (Vera et al., 2011). For example, the seaweed polysaccharides ulvan, carrageenan, alginate, and laminarin improved total polyphenol and lignin contents, inhibited fungal growth, and reduced Verticillium wilt in olives (Salah et al., 2018). Extract of *A. nodosum* increased the activity of peroxidase, polyphenoloxidase and other enzymes, and several pathogenesis-related proteins in carrots, resulting in enhanced resistance to *Alternaria radicina* and *Botrytis cinerea* (Jayaraj et al., 2008). In a different study, laminarin suppressed scab (*Venturia inaequalis*) in apple by inducing plant resistance, but supplemental fungicidal applications were necessary to achieve the desired control (Van Hemelrijck et al., 2013). Foliar application or seed treatment with the extracts of brown algae *Cystoseira myriophylloides*, *Fucus spiralis*, and *Laminaria digitata* significantly reduced disease severity by *V. dahliae* and *Agrobacterium tumefaciens* in tomato through induced resistance (El Modafar et al., 2012).

Many botanical extracts are primarily used as biopesticides rather than biostimulants. Some products based on soybean and other vegetable oils are used as both biostimulants and biopesticides. However, in general, there are fewer examples where botanicals have been used exclusively as biostimulants and have indirectly contributed to pest or disease suppression. Willow bark extract, which is used as a plant growth regulator and biostimulant, also has fungicidal properties (Deniau et al., 2019). Treating potato with Canada milkvetch extract, *P. fluorescens* DF37, and *B. pumulis* M1 provided up to 84% of *Verticillium* control with up to 24% of yield increase (Uppal et al., 2008), but it was not clear whether the disease suppression was a result of biostimulation or the pesticidal activity of these materials.

6.6 Silicates and phosphites

Sodium silicate inhibited conidial germination and mycelial growth of *Fusarium sulphureum* in controlled dry rot of potato tubers (Li et al., 2009). Calcium silicate reduced downy mildew (*Peronospora manshurica*) in soybean (Nolla et al., 2006), and when applied with calcium chloride, white mold (*Sclerotinia sclerotiorum*) in dry beans (Paula Júnior et al., 2009). Foliar application of silicates might act as a physical barrier to pathogen infection, but root application of potassium metasilicate increased plant defenses and controlled downy mildew (*P. xanthii*) in cucumber (Liang et al., 2005). Silicon, along with *G. mosseae* and *Enterobacter* sp. UPMSSB7, suppressed white root rot caused by *Rigidoporus microporus*, similar to a fungicide treatment, while improving various growth parameters of rubber seedlings (Shabbir et al., 2021).

In addition to its nutritional importance, phosphite has a significant influence on disease suppression. Föster et al. (1998) reported a significant reduction in root and crown rot caused by *Phytophthora capsici* in pepper plants treated with phosphite. Shearer and Fairman (2007) observed that phosphite application resulted in a significant reduction in the mortality of *Banksia* spp. from *Phytophthora cinnamomi* infection. Silva et al. (2011) reported yield improvement and downy mildew reduction in soybean from potassium phosphite application. They also observed that potassium phosphite application supplemented with fungicidal treatments significantly controlled Asian soybean rust caused by *Phakospora pachyrhizi* and powdery mildew caused by *Microsphaera diffusa*. In another study, Zhao et al. (2013) found that applying phosphorus oxyanion solution to sweet oranges with huanglongbing, caused by *Candidatus Liberibacter* spp., reduced the severity of disease symptoms and significantly improved fruit yields.

6.7 Chitosan

Numerous studies have demonstrated the effect of chitosan on improved enzymatic activity, production of phytoalexins and pathogenesis-related proteins, lignin synthesis, and enhanced plant defenses, resulting in reduced disease incidence and increased postharvest quality (El Hadrami et al., 2010). Pichyangkura and Chadchawan (2015) thoroughly reviewed the plant protection offered by chitosan from several studies in vegetables, fruits, and ornamentals.

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Control of *F. oxysporum* f. sp. *radices-lycopersici* (Lafontaine and Benhanou, 1996) and *Xanthomonas gardneri* (Jail et al., 2014) in tomato, *Alternata*, *Fusarium avenaceus*, *F. culmorum*, *Epicoccum purpurascens*, and *S. sclerotiorum* in lemon balm (Szczeponek et al., 2006), *B. cinerea* and *P. viticola* in grapes when applied with copper sulfate (Aziz et al., 2006), *Colletotrichum capsici* in bell pepper during postharvest storage when applied with lemongrass oil (Ali et al., 2015), *Aspergillus flavus* (De Oliveira Pedro et al., 2013), *Aspergillus ochraceus* (Meng et al., 2020), and *Phytophthora infestans* (Huang et al., 2021) *in vitro*, and *F. oxysporum* in potato (Ren et al., 2021) are some of the examples of chitosan application in disease management.

7 Suppression of arthropod pests

7.1 AMF and other microorganisms

AMF can have an impact on herbivore damage by modifying the morphological and biochemical characters of the plant by augmenting defense mechanisms and imparting resistance. A recent review by Selvaraj and Thangavel (2021) discussed the role of AMF as a part of IPM against pest insects. Coppola et al. (2019) found that *Trichoderma atroviride* P1 in tomato contributed to the control of Egyptian cotton leafworm, *Spodoptera littoralis*, and the potato aphid, *Macrosiphum euphorbiae*, through direct and indirect defense mechanisms. An increased oxidative burst reaction and the production of volatile organic compounds that attract the parasitoid *Aphidius ervi* parasitizing aphids, and an enhanced production of protective enzymes against the leafworm, were found to be the defense mechanisms. A similar impact of increased defenses and attraction of *A. ervi* to parasitize *M. euphorbiae* was also seen in tomato from *T. harzianum* application, in an earlier study (Coppola et al., 2017). Some species of *Trichoderma* and their strains can also control pest insects through entomopathogenic activity. For example, *T. atroviride*, *Trichoderma citrinoviride*, and *T. harzianum* inhibited 73–85% of egg hatch in the bean weevil *Acanthoscelides obtectus*, and the polyphagous long-horned beetle *Xylotrechus arvicola* (Rodríguez-González et al., 2017). A *Trichoderma* sp. alone and in combination with *Bacillus thuringiensis* effectively controlled the brinjal shoot and fruit borer *Leucinodes orbonalis*, the cotton aphid *Aphis gossypii*, and the cotton leafhopper *Amrasca biguttula biguttula* (Nawaz et al., 2020). *Trichoderma longibrachiatum* controlled *L. orbonalis* and increased eggplant yields by 56% (Ghosh and Pal, 2016).

7.2 Plant growth-promoting rhizobacteria

As the inducers of plant defense mechanisms, PGPR elicit responses that influence herbivore infestations. While some PGPR may have entomopathogenic properties, most of them suppress pest populations through ISR (Disi et al., 2019). For example, Zehnder et al. (1997) reported that when cucumber plants were treated with *B. pumilus* INT-7, feeding damage by the cucumber beetle, *Diabrotica undecimpunctata howardi*, and the bacterial wilt caused by *Erwinia tracheiphila*, which the beetle transmits, were significantly reduced due to the increased synthesis of cucurbitacin. In cotton, treating plants with *Bacillus* spp. resulted in higher levels of gossypol and jasmonic acid, leading to reduced larval feeding of the beet armyworm *Spodoptera exigua* (Zebelo et al., 2016). In peppermint, treatment with *B. amyloliquefaciens* GB03 and *P. putida* SJ04 increased salicylic and jasmonic acid levels and essential oil production, similar to the response from the feeding of the sunflower looper *Rachplusia nu* (del Rosario Cappellari et al., 2020). Although this study did not measure the impact of PGPR on herbivores or herbivory, it demonstrated that PGPR elicit defense responses. Several studies also demonstrated the influence of PGPR on natural enemies. In arugula, treatment with *B. amyloliquefaciens* GBO3 and the presence of the fall armyworm *Spodoptera frugiperda*, and the diamondback moth *Plutella xylostella*, influenced the behavior of the predatory earwig *Doru lutiepes* (Bell et al., 2020). The presence of PGPR and herbivore damage had a synergism in attracting earwigs. In rice, reduced leaf folder damage and increased natural enemy activity were seen from the inoculation of *P. fluorescens* (Saravanakumar et al., 2008). Similarly, *P. fluorescens* WCS417r colonization of the thale cress *Arabidopsis thaliana* increased the activity of the parasitoid *Microplitis mediator* when the plants were infested with the cabbage moth *Mamestra brassicae* (Pangesti et al., 2015). PGPR suppressed the production of herbivore-induced terpene, methyl salicylate, and lilial, and enhanced plant growth and ISR.

7.3 Humic substances

A review by Joshi et al. (2015) presented several examples of insect control with vermicompost or vermiwash applications. Aphids, beetles, earworms, hornworms, mealybugs, and mites were controlled on cabbage, corn, cucumber, eggplant, mustard, pepper, and tomato in multiple studies. Humic acid also controlled the root-knot nematode *Meloidogyne incognita*, *in vitro* and *in situ*, and promoted banana growth (Seenivasan and Senthilnathan, 2018).

7.4 Algal and botanical extracts

Some algal and botanical extracts have both biostimulatory and insecticidal properties. It can be difficult to distinguish their roles in certain situations, but some examples will be discussed where biostimulants have an impact on arthropods. An earlier report by Stephenson (1966) indicated the indirect impact of a hydrolyzed seaweed product on aphids, red spider mites, and plant diseases, through increased plant resistance. Eckol, a phenolic extract of the brown seaweed *Ecklonia maxima*, increased various growth parameters, enzymatic activity, chlorophyll, carotenoid, and proline content, and reduced aphid infestations (Rengasamy et al., 2016). Increased myrosinase activity was responsible for the population reduction in the cabbage aphid *Brevicoryne brassicae*. González-Castro et al. (2019) found repellent and insecticidal properties of the extracts of the macroalgae *Caulerpa sertularioides*, *Laurencia johnstonii*, and *Sargassum horridum* against the Asian citrus psyllid *Diaphorina citri*.

Juglone, a quinoid compound extracted from walnut trees, has biostimulatory, algacidal, bactericidal, fungicidal, insecticidal, and herbicidal properties (Islam and Widhalm, 2020). Azadirachtin, which is commonly used as an insecticide and insect growth regulator, also has a biostimulatory effect (Dara, 2021).

7.5 Silicates and phosphites

Silicates applied as fertilizers benefit plants by strengthening the tissues and acting as a mechanical barrier, and also trigger immune responses. Numerous studies have demonstrated a significant reduction in arthropod populations and their damage from silicate applications (Laing et al., 2006; Moraes et al., 2019). Some of the mechanisms of resistance offered to plants by silicon include the reduced penetration of plant tissues, increased wearing of mouthparts, reduced digestibility and palatability of plant material, and damage to the insect's midgut epithelium (Alhousari and Greger, 2018). Additionally, soluble silicon in plants also attracts natural enemies and enhances the biocontrol of pests (Bakhat et al., 2018). For example, silicic acid application reduced damage by the cucurbit beetle *Diabrotica speciosa*, made the plants less preferable, and increased plant growth in potato without affecting their natural enemies (De Assis et al., 2012). Potassium silicate supplementation for chrysanthemum reduced 54% of mining by the American serpentine leafminer *Liromyza trifolii*, although it also reduced the plant height by 10% (Klittich and Parrella, 2014). Silicon application through irrigation significantly reduced the numbers of twospotted spider mites (*Tetranychus urticae*) and the levels of powdery mildew (*Podosphaera aphanis*) in strawberry (Liu et al., 2020a).

Similar to silicates, phosphites also have an impact on pest suppression. Foliar application of potassium phosphite in potato reduced the number of potato tuber moth (*Phthorimaea operculella*) larvae by more than 50%, without affecting parasitoid populations (Mulugeta et al., 2018). Similarly, foliar application of a phosphite fungicide containing sodium, potassium, and ammonium phosphites reduced the survival and prolonged the development of the Colorado potato beetle (*Leptinotarsa decemlineata*), and reduced the foliar damage while controlling diseases (Patterson and Alyokhin, 2014).

7.6 Chitosan

Chitosan has the potential to control multiple pests including arthropods. Derivatives of chitosan had significant insecticidal activity against *S. littoralis* (Rabea et al., 2005), *B. brassicae*, the oleander aphid *Aphis nerii*, and the wheat aphid *Schizaphid graminum* (Sahebzadeh et al., 2017) in laboratory assays. Colloidal chitosan from seafood waste showed significant antifeedant activity against *S. frugiperda* and reduced the feeding damage (Moorthy et al., 2021). Zhang and Tan (2003) reported insecticidal activity of chitosan against the cotton bollworm (*Helicoverpa armigera*), *P. xylostella*, *S. exigua*, the bird-cherry oat aphid (*Rhopalosiphum padi*), *A. gossypii*, the grain aphid (*Sitobion avenae*), the green peach aphid (*Myzus persicae*), the mealy plum aphid (*Hyalopterus pruni*), and the rose-grain aphid (*Metopolophium dirhodum*), with very high mortality in some species. Alfy et al. (2020) found that chitosan nanoparticles were effective against *S. littoralis*, the desert locust *Locusta migratoria*, and *M. incognita*. Fan et al. (2020) also reported that fluorinated derivatives of chitosan effectively killed the second-instar larvae and inhibited the egg hatch of *M. incognita*.

Chitosan is not only used for its direct and indirect effect on pest suppression. Its role as a nanocarrier of pesticides for safe and targeted delivery is also explored (Maluin and Hussein, 2020). For example, chitosan helped improve RNA interference efficacy against *S. frugiperda* (Gurusamy et al., 2020). Chitosan was also used for the controlled release of spinosad for increased environmental durability (Li et al., 2020). The monoterpenes carvacrol and linalool, nanoencapsulated in chitosan, increased the control efficacy against the pests *H. armigera* and *T. urticae* (Campos et al., 2018). In a different study, chitosan alone and as chitosan-reduced silver nanocrystals were detrimental to *H. armigera* (Murugan et al., 2021).

8 Tolerance to abiotic stresses

When plants undergo abiotic stresses such as salinity and drought, they are more vulnerable to pests and diseases. If biostimulants can improve plant growth under abiotic stresses, plants can use their resources to withstand biotic stresses. At the same time, plant stresses can also influence soil microbial populations (Liu et al., 2020b). For example, *G. mosseae* increased the salt tolerance of citrus seedlings with improved plant and root growth, photosynthesis, and ionic balance (Wu et al., 2010). *G. versiforme* stimulated plant growth and improved biomass of tangerine under water stress (Wu and

Xia, 2006). Improved nutrient absorption, higher accumulation of carbohydrates in roots and foliage, change in root plasticity, and higher antioxidative enzyme activity were among the factors that were found to impart salt and drought tolerance (Wu and Xia, 2006; He et al., 2007; Wu et al., 2010). Dual inoculation of *Rhizobium* sp. and *Enterococcus mundtii* increased seed germination, plant height, biomass, chlorophyll content, and nutrient uptake in mung bean growing in saline conditions (Kumawat et al., 2021).

Plant-derived protein hydrolysates improved plant growth, nutrient utilization, and yields of lettuce growing in pots under saline conditions (Lucini et al., 2015). The diameter of grapes was significantly improved, even under water-stressed conditions, when a protein hydrolysate was applied (Meggio et al., 2020). Although the differences were not significant, protein hydrolysates helped maintain the weight and number of fruit clusters under water stress.

Canellas et al. (2015) discussed the role of humic substances in regulating secondary metabolism and alleviating various stresses. Increasing the accumulation of phenolic compounds, improving osmoregulation, and regulating peroxidase activity are among the various influences of humic substances on plants. Similarly, macroalgae-based biostimulants also stimulate the production of plant defense mechanisms and other physiological responses that alleviate stress (Sharma et al., 2014). Silicate fertilizers increase the yield, quality, and shelf-life of grapes grown in calcareous gray desert soil (Zhang et al., 2017). Phosphites induce adaptive plant responses to various stresses and improve plant performance (Trejo-Téllez and Gómez-Merino, 2018). For example, under heat stress, phosphite induced the accumulation of stress proteins, reduced oxidative stress, and maintained photosynthetic efficiency in potato seedlings (Xi et al., 2020).

9 Multitrophic interactions and influencing factors

The effect of biostimulants can vary widely depending on various factors. In addition to neutral and positive effects, some biostimulant materials can negatively impact growth and yields (Nardi et al., 2016). AMF *Glomus caledonium*, *Glomus fasciculatum*, and *G. mosseae* increased the number of leaves per plant in the oxeye daisy *Leucanthemum vulgare* but influenced the levels of parasitism of the ragwort leafminer *Chromatomyia syngenesiae*, by *Diglyphus isaea* (Gange et al., 2003). Depending on the AMF species and their combinations, parasitism was higher, lower, or neutral in AMF-colonized plants. *Trichoderma* spp. that produce the volatile organic compound trichodiene, suppressed plant defenses and increased the emergence of *A. obtectus* and its damage to beans (Rodríguez-González et al., 2018). Application of glycine betaine did not improve strawberry fruit yields, but a product containing nutrients and humates improved yields by 11% (Dara, 2019d). Soy protein hydrolysate improved strawberry yields when applied alone but not in combination with a product containing *T. harzianum* and *T. virens* (Dara, 2020). A product containing soybean and corn oils stunted strawberry plant growth and reduced yields, probably from higher application rates (Dara, unpublished data). Similarly, an animal-derived protein hydrolysate reduced the weight of daughter plants in strawberry (Lisiecka et al., 2011). Seedling growth of cucumber was inhibited but the single-fruit weight and concentration of certain nutrients in shoots increased with *G. versiforme* (Wang et al., 2008). Overapplication of silicates reduced flower yields and caused growth abnormalities in ornamentals (Kamenidou et al., 2008).

Certain practices and other agricultural inputs might not be compatible with some biostimulants, especially if they have live microorganisms and require special storage, handling, and application. Both the biostimulant industry and the grower community should be aware of the potential negative impacts of biostimulants and work with the researchers to determine rates, frequencies, and application strategies that are appropriate for their crop situation.

10 Strategies of using biostimulants

Although numerous studies have demonstrated the potential of biostimulants in improving crop growth, health, and yields, it is always advisable to consider IPM or integrated crop management approaches that take advantage of multiple strategies and reduce the reliance on one or a few options. Arthropod pests and plant pathogens continuously evolve and develop resistance to various agricultural inputs, especially those that have pesticidal properties. Since some biostimulants also have a certain level of pesticidal properties, a continuous monitoring of potential negative interactions in the environment and an adjustment of the strategies as appropriate are recommended. In general, biostimulants can be used as seed or transplant treatments, or they can be applied throughout the crop cycle as seed treatments, to the soil, or as foliar sprays (Fig. 2). Based on several studies discussed in this chapter, biostimulants improved tomato seed germination, root and shoot growth, general health, yield, quality, and nutritional value, suppressed various pests and diseases, improved biocontrol activity, and reduced the need for synthetic fertilizers and the potential use of pesticides (Fig. 3). Using tomato as a model plant, the importance of biostimulants can be demonstrated in crop production and crop protection. In general, biostimulant supplements can enhance the current agronomic practices and build plant resilience to various biotic and abiotic stresses.

Building soil health should be one of the priorities for sustainable agriculture, and biostimulants play a major role in this area by adding organic matter, beneficial microorganisms, nutrients, and other essentials to the soil.

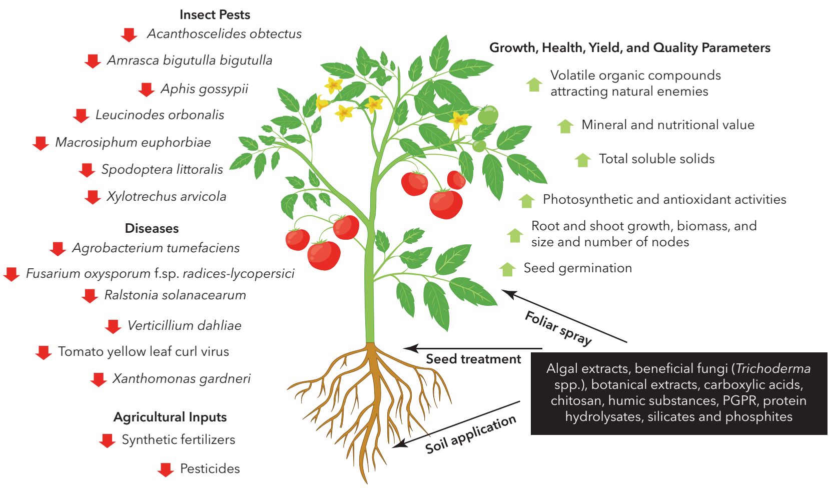

Figure 3 Tomato as a model crop for improving growth, health, yield, and parameters, and suppressing pests and diseases based on the various studies reviewed in this chapter.

It helps growers and crop care professionals to have a thorough knowledge of various biostimulants, their modes of action, interactions with other biotic and abiotic inputs and farming practices, and their indirect effect on pest and disease management. Biostimulants are part of a proactive strategy for maintaining plant health, while pesticides are curative measures to address specific issues. In other words, biostimulants are comparable to probiotics and vitamins, while pesticides are comparable to the medicines that humans take. Since biostimulants help improve nutrient uptake and trigger plant defenses against stressors, they contribute to the reduction of fertilizer and pesticide use and provide additional benefits beyond improved plant growth and yields. Modern-day agriculture can significantly benefit from incorporating biostimulant use as a good agricultural practice.

11 Challenges and future needs

Unlike the immediate effects of some fertilizer or pesticide inputs, the positive impact of biostimulants may not be as obvious and could easily be attributed to other crop production and protection practices. Additionally, the biological nature of several biostimulants also adds to the general misconception that biologicals are slow and less effective than synthetic agricultural inputs. The higher cost of some biostimulants and a lack of convincing applied research data are critical hurdles for the increased adaptation of biostimulants in many cropping systems. Based on the new IPM model and its emphasis on research, outreach, information management, and communication (Dara, 2019b), the future needs for integrating biostimulants as a critical part of crop production and IPM are as follows:

1. Develop collaborations among researchers, biostimulant manufacturers, and growers for conducting applied research and continuously generating data from various crop and field situations.
2. Understand various interactions among biostimulants, other agricultural inputs, agricultural practices, plants, arthropods, and microorganisms, and develop appropriate storage, handling, and use strategies.
3. Incorporate biostimulants as a part of cultural control of IPM.
4. Effectively disseminate the research findings through outreach activities and encourage improved communication among key players for building confidence and refining use strategies.
5. Invest in research to improve their formulations and their efficacy while optimizing their cost.

12 Conclusion

This chapter, probably the first of its kind, provided an overview of various biostimulant categories and how they can be used in improving plant growth, health, and yields, especially as a part of an IPM program (Fig. 2). Depending on the strain, source, form, formulation, application rates, and other factors, some of the biostimulants might be commercially available as biopesticides or biofertilizers. While biostimulatory and biopesticidal properties overlap for some biostimulant active ingredients, the main objective was to present the biostimulatory properties and the indirect effect of various active ingredients on arthropod pests, plant pathogens, and in some cases, plant-parasitic nematodes. With a growing interest in biostimulants and their potential, as well as the continued demand for sustainable food production, biostimulant use is expected to increase further in the near future.

13 Where to look for further information

13.1 Further reading

- Integrated pest and disease management in greenhouse crops (Springer) by Gullino et al. (2020).
- Biostimulants for sustainable crop production (Burleigh Dodds Science Publishing) by Youssef Rouphael et al. (2020).
- Biopesticides in organic farming: recent advances (Taylor and Francis) by Awasthi (2021).

13.2 Key journals/conferences

- eJournal of Entomology and Biologicals (https://ucanr.edu/JEB).
- Frontiers in Sustainable Food Systems (https://www.frontiersin.org/journals/sustainable-food-systems).
- Journal of Economic Entomology (https://academic.oup.com/JEE).
- Entomological Society of America annual meetings (https://entsoc.org).

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