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Review

Survey of the Influences of Microbial Biostimulants on Horticultural Crops: Case Studies and Successful Paradigms

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Abstract: Sustainable farming of horticultural plants has been the focus of research during the last decade, paying significant attention to alarming weather extremities and climate change, as well as the pressure of biotic stressors on crops. Microbial biostimulants, including plant growth-promoting bacteria (PGPB) and arbuscular mycorrhizal fungi (AMF), have been proven to increase plant growth via both direct and indirect processes, as well as to increase the availability and uptake of nutrients, boosting soil quality, increasing plants' tolerance to abiotic stress and increasing the overall quality attributes of various horticultural crops (e.g., vegetables, fruit, herbs). The positive effects of microbial biostimulants have been confirmed so far, mostly through symbiotic interactions in the plant–soil–microbes ecosystem, which are considered a biological tool to increase quality parameters of various horticultural crops as well as to decrease soil degradation. However, more research is needed to address future challenges of crop production through revealing the mechanisms of action and identifying response patterns of crops to various microbial products. The present review aims to present the most up-to-date results regarding the practical applications of microbial biostimulants in horticultural species, including case studies of successful paradigms for the most important microbial genera of PGPB and AMF. Moreover, the mechanisms of the actions are briefly described while future remarks are also discussed, aiming to suggest further needs to be addressed for the successful establishment of microbial biostimulants in sustainable horticultural crop production.

Keywords: sustainability; *Rhizobium*; *Mycorrhizas*; *Azospirillum* spp.; *Azotobacter* spp.; plant growth-promoting rhizobacteria; arbuscular mycorrhizal fungi

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1. Introduction to Microbial Biostimulants

There is an increasing demand to apply ecofriendly technological tools in crop production that will ensure the sustainability of agricultural production systems in the mid- and long-term [1]. However, the adversely changing climate conditions put at risk crop yields and threaten global food security [2,3]. Biostimulants can be applied to complement the use of chemical inputs, including the use of beneficial rhizosphere microbiome like plant growth-promoting rhizobacteria and advantageous fungi [4–8]. Biostimulants based on microorganisms is a subgroup of the heterogeneous family of biostimulants and refers to the microorganism (or mix of microorganisms) that can stimulate physiological and biochemical processes that benefit nutrient uptake, nutrient efficiency, increase tolerance to abiotic stress, crop quality, and/or yield of plants [9], which can moderately mitigate the damaging impacts of intensive agriculture [10–12]. These microbial biostimulants can be classified as formulations of microorganism or microbial consortia when applied to plants through seed, foliar or rhizosphere application [13,14]. The application of beneficial microbes can change the biological structure of the soil and promote the growth of other beneficial microbes that further increase soil fertility and lead to higher crop yield, as well as contribute to the replenishment of the normal microflora of soil [14,15]. Moreover, they may affect shoot targets via the regulation of stomata and xylem hydraulic conductance, root targets via root zone water availability, root ethylene and auxin levels, as well as the whole plant responses through ROS scavenging, osmoprotection and membrane stability [16].

The most common microorganisms included in this group of biostimulatory products are the non-pathogenic and non-toxigenic bacteria of *Rhizobium* spp., *Azotobacter* spp., and *Azospirillum* spp., as well as various mycorrhizal fungi [11]. The biofertilizers and biocontrol factors currently in use in crop production are mostly related to a group known as plant growth-promoting rhizobacteria (PGPR) [17,18], which are a very heterogeneous group of endophytic bacteria consisting of the phyla *Proteobacteria*, *Actinobacteria*, *Firmicutes*, and *Bacteroidetes* [19,20]. The most well-known PGPR belong to the genera *Alcaligenes*, *Azospirillum*, *Arthrobacter*, *Azotobacter*, *Bacillus*, *Enterobacter*, *Burkholderia*, *Klebsiella*, *Pseudomonas*, *Rhizobium* and *Serratia* [21]. There are several PGPR-derived products commercially available for biocontrol based on strains of *Bacillus* and *Pseudomonas* and *Streptomyces griseoviridis* [22]. Therefore, plant growth-promoting rhizobacteria suggest a promising means to develop a productive and sustainable agricultural sector in spite of the impact of environmental stressors, since they can lead to higher plant growth and yield via the production of phytohormones, antioxidants, osmolytes, volatile compounds, exopolysaccharides and 1-aminocyclopropane-1-carboxylate deaminase [23].

On the other hand, arbuscular mycorrhizal fungi (AMF) are growth stimulants, nutrient-enriching and phytoremediative bio-factors which provide protection to plants from diseases and resistance against salinity, drought, and heavy metal toxicity [24]. The application of AMF is recommended in improving crops' performance, since they are commonly found in over 90% of plant species; however, many customary agricultural applications, such as fertilization and tillage, can decrease the abundance of AMF in the soil with negative effects on plant functions [25]. There are various biofertilizers and biocontrol products based on mycorrhizal fungi available now, including mainly strains of *Glomus* sp., as well as other mycorrhizal inoculants such as the spores of *Funneliformis mossae*, *Rhizofagus irregularis*, and *Claroideoglomus etunicatum* [26]. Arbuscular mycorrhizal fungi, classified in the Phylum Glomeromycota, are mandatory symbionts that consist of three different classes (*Archaeosporomycetes*, *Glomeromycetes*, and *Paraglomeromycetes*), five orders (*Arachaeosporales*, *Gigasporales*, *Diversisporales*, *Glomerales*, and *Paraglomerales*), 14 families, 29 genera, and more than 200 species [27–30]. They are commonly found in the root systems of plants and increase growth, nutrient absorption and biomass production under stressful or optimum conditions [31]. Moreover, AMF application has been proven as a profitable practice for various horticultural plants such as apple, pepper, citrus, peach, lettuce, strawberry, onions, pineapple, and melon [32,33]. Similarly, *Bradyrhizobium japonicum*, *Stenotrophomonas rhizophia*, *Hyalangium minutum*, *Variovorax paradoxus*, and *Paenibacillus macerans* have positively and directly influenced the bacterial activity of the plant rhizosphere, indicating that they would be appropriate for use in sustainable and organic farming [34]. Therefore, the employment of a mixture of PGPRs and AMFs is a promising plant growth-promoting tool, which combines the benefits of these groups of microorganisms and also involves their synergistic effects [20]. Emmanuel and Babalola [35] reported that the benefits of co-inoculation of plant growth-promoting bacteria (PGPB) and arbuscula mycorrhizal fungi (AMF) were higher for the yield and quality of horticultural crops than single applications.

However, although microbial biostimulants are an innovative and promising group of agricultural inputs, they still remain unexplored from most farmers. Therefore, more effort is needed to suggest and introduce them as an environmentally sustainable approach to increase crop production and health, contributing substantially to making the 21st century the age of biotechnology [36]. The utilization of microbial biostimulants may also support the sustainability aspect in medicinal and aromatic plant cultivation, as for example basil production (*Ocimum basilicum* L.), particularly under growth-limiting environments [37]. Plant-associated bacteria may interact with their environment, and bacterial volatile compounds can modulate plant hormones, increase stress tolerance, plant growth, aroma, crop quality and nutraceutical parameters, and decrease post-harvest damages, thus improving medicinal and aromatic crops performance under stress conditions [38,39].

The aim of this literature review is to survey the effects of microbial biostimulants by presenting case studies and successful paradigms in various horticultural crops. Moreover, the main mechanisms of action of the various biostimulant products are briefly described, while a special section suggesting the future needs that should be addressed for the successful integration of microbial-based biostimulant products in horticultural crop production is also provided. The information provided is obtained from review articles, randomized control experiments, and analytical observations and studies which were gathered from different literature sources such as Google Scholar, Scopus, Science Direct and PubMed. The keywords used were the Latin and common names of various horticultural species, microbial biostimulants, mycorrhizas, *Azospirillum* spp., *Azotobacter* spp., as well as the scientific names of other plant growth-promoting rhizobacteria.

2. Mechanisms of Microbial Biostimulant Action

The mechanisms of action of microbial plant growth promoters are divided into direct and indirect ones. Direct mechanisms suggest that microbes are active in the synthesis of substances that can increase the uptake of nutrients, while indirect ones include, among others, zinc solubilization, siderophore production, indole acetic acid biosynthesis, phosphorus solubilization, ammonia and hydrogen cyanide production, antioxidant enzyme production, phytohormone production, and biological nitrogen fixation [40,41]. The negative impacts of environmental stresses could be mitigated by the application of microbial biostimulants such as fungi and bacteria via producing hormone-like stimulants with positive effects on plant growth [42]. Moreover, the protective effects of microbial biostimulants on plants against various stressors include the regulation of molecular processes that are involved in the interaction of plants with microorganisms and induce the biosynthesis of secondary metabolites [43]. The production of these protective molecules is achieved through the shikimate pathway that involves the enzyme Phenylalanine Ammonia Lyase (PAL) for the production of phenylpropanoids after microbial eliciting [44], which plants facilitate to cope with pressure from external factors and is known as induced systemic resistance (ISR) [45]. The main mechanisms addressed by microorganisms based on biostimulants are indicated in Figure 1. Figure 2 shows the impact of both foliar and soil on applications of various biostimulants such as humic substances, microorganisms, seaweed extract and protein hydrolysates on plant phenotype, cellular level, and molecular level.

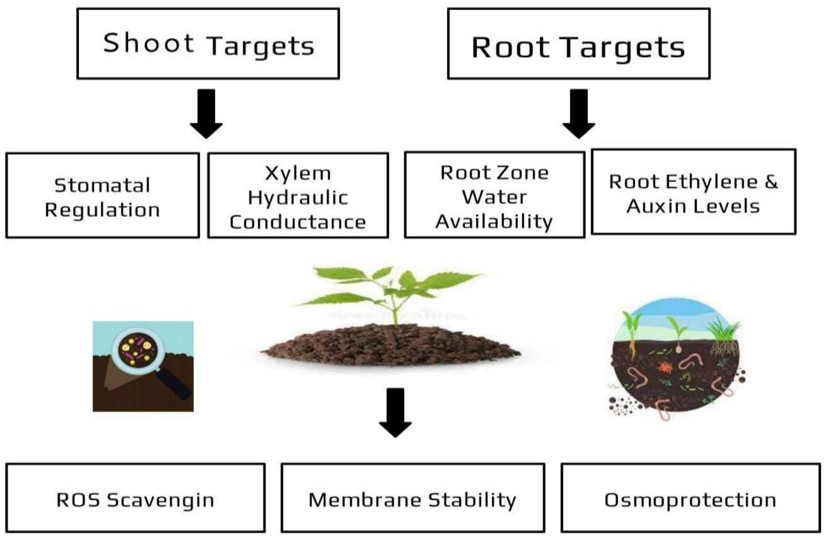

Figure 1. The principal mechanisms targeted by microorganisms based of different biostimulants.

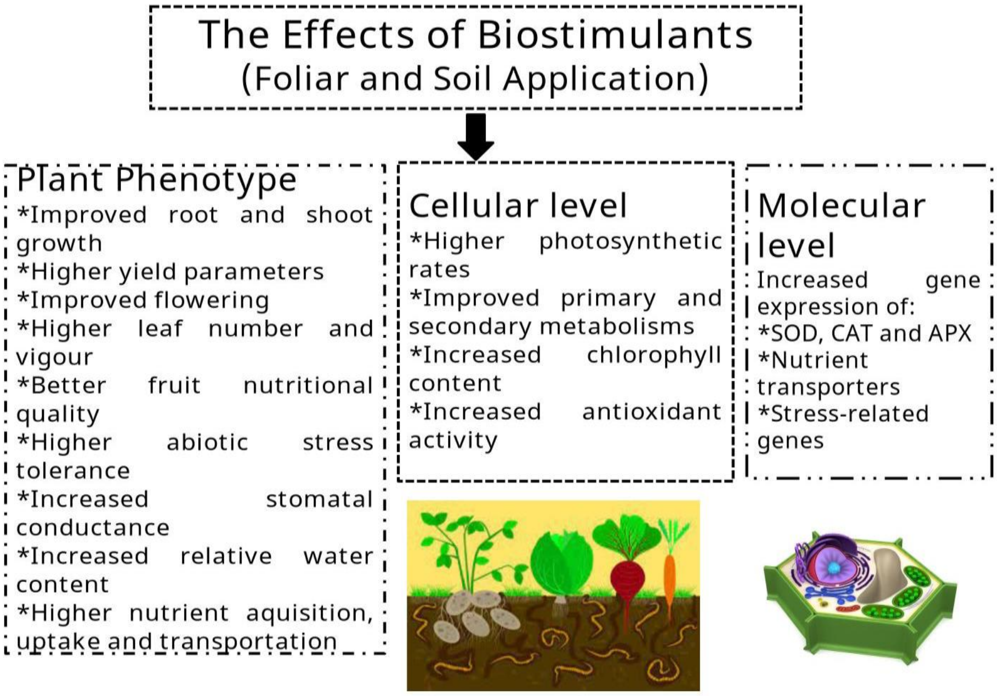

Figure 2. The most notable impacts of different biostimulants on plant phenotype, cellular level and molecular level.

2.1. Modes of Action of Plant Growth-Promoting Rhizobacteria

Modes of action of plant growth-promoting rhizobacteria (PGPR) involve the induction of synthesis of biosurfactants and chelating factors, avermectins, secondary metabolities, fluorescent insecticidal toxins, beta-glucanases, and chitinases for disease resistance. Additionally, they may promote antioxidant activity and biosynthesis of phytochemicals, modulate the metabolism, synthesis and accumulation of anthocyanins, polyphenols and vitamin C, which finally results in quality improvement in the crop products. Other modes of action suggest the biosynthesis of cytokinins, ABA, ethylene, auxins, gibberlins, exopolysaccharides, organic acids and siderophores; the upregulation of stress-related genes; the expression of antioxidant enzymes activity; and the activation of growth promoting genes [46]. The application of plant growth-promoting bacteria may enrich soil with bacterial inoculums which improve nutrients' supply (e.g., phosphate and potassium solubilizing bacteria), improve immunity against abiotic stressors through the induction of 1-aminocyclopropane 1-carboxylate (ACC) deaminase, amino acids, soluble sugars, and antioxidants like peroxidases (POD), catalases (CAT), superoxide dismutase (SOD), and ascorbate peroxidases (APX) [47,48]. The production of ACC deaminase, which catalyzes the conversion of ACC to α-ketobutyrate and ammonia, is also beneficial to plants when subjected to stress conditions since ACC is the precursor of ethylene which has adverse effects on plants [49]. Stress conditions are associated with oxidative stress and the induction of reactive oxygen species; therefore, plants accumulate antioxidant compounds such as phenolic compounds, organic acids, tocopherols, terpenoids, etc., or non-enzymatic antioxidants (e.g., proline, glycine-betaine) that help them to mitigate stress through scavenging of oxidative radicals [50–52].

In abiotic stress conditions such as drought, salinity, heavy metals, heat and cold stress, PGPR biostimulants lead to N_2 fixation, P solubilization, the synthesis of volatile organic compounds (VOCs) and aminoacids, phytochrome modulation, and the production of siderophores and exopolysaccharides [47]. Moreover, they regulate phytohormone signaling via the synthesis of hormones such as TAA, cytokinin, gibberllins, ethylene, and ABA; induce antioxidant defense mechanisms, the accumulation of osmolytes, ROS scavenging, and lipid peroxidation inhibition; regulate the transcription and the expression of stress-related genes; or photosynthetical processes and morphological responses of plants to abiotic stress [47]. For example, Pellegrini et al. [53] reported that the application of *Azospirillum brasilense*, *Gluconacetobacter diazotrophicus*, *Burkholderia ambifaria* and *Herbaspirillum seropedicae* induced the production of plant hormones that had a positive role in solubilization and uptake of nutrients in onion plants. Similarly, *Azospirillum brasilense* (Sp7b and Sp245b) induced the production of substantial amounts of phytohormones such as IAA, and enhanced germination, root length, root weight, and vigor index of germinating seeds in cucumber, tomato and lettuce [54]; *Bacillus pumilus*, *Bacillus Amyloliquefaciens*, *Bacillus mojavensis*, and *Pseudomonas putida* induced the synthesis of indole-3-acetic acid N2-fixation and P solubilization, and improved growth, production and nutrient uptake of tomato plants [55].

Regarding the alleviation of pressure on plants from biotic stressors, the application of natural microbial biostimulants which are obtained from metabolites of soil microorganisms is an appropriate technique, not only to increase crops' performance but also to protect plants from various diseases [56,57]. The mode of action of *Bacillus cereus* (PX35), *Serratia* sp. XY21, and *Bacillus subtilis* SM21 against root-knot nematodes in tomato plants was to improve plant resistance via synergistic control [58]. On the other hand, the application of *Pseudomonas aeruginosa* LV improved resistance to bacterial stem rot in tomato plants via the accumulation of extracellular bioactive compounds such as proteins, defensins, phytoalexins, phenolics, and flavonoids [59]. In the case of ginger plants, *Bacillus cereus*, *Bacillus subtilis* BSP, and *Bacillus* BSV increased resistance against blister blight through the production of 1-ACC [60]; while both *Bacillus safensis* and *Bacillus altitudinis* increased resistance of cabbage to black rot via IAA production [61].

2.2. Modes of Action of Arbuscular Mycorrhizal Fungi

In the case of AMF, Rouphael et al. [51] concluded that the increase in biomass of crops after the application of two beneficial fungi, namely arbuscular mycorrhizal fungi (AMF) and *Trichoderma koningii* TK7, could be associated with the modulation of the multilayer phytohormone interaction network, as well as a potential increase in nitrogen use efficiency via the Glutamine Oxoglutarate Aminotransferase (GS-GOGAT) system. Moreover, Hashem et al. [52] reported that the adverse impacts of salt stress in cucumber were ameliorated by AMF inoculation that increased the activity of antioxidant enzymes which scavenged ROS and protected plant tissues from dehydration stress, including catalase, ascorbate peroxidase, and superoxide dismutase, plant biomass and the synthesis of pigments, proline, glycine betaine. Similarly, Shekoofeh et al. [62] reported that AMF inoculation protected Ocimum basilicum plants against salinity stress by increasing water use efficiency, and improved chlorophyll synthesis and mineral uptake. Balliu et al. [63] and Yuan et al. [64] also indicated that inoculation of tomato plants with AMF increased the contents of potassium, nitrogen, phosphorous and calcium in leaves, thus indicating an improved nutrients uptake and translocation, while the same practice may increase photosynthetic parameters such as net photosynthesis and stomatal conductance, also root growth, and result in improved nutrient uptake and water use efficiency [65]. Other examples of modes of action of AMFs include: the increased antioxidant activity and the accumulation of osmolytes [66]; the upregulation of proline biosynthesis [66,67]; and the accumulation of Mg, Ca and K which promoted chlorophyll production and increased the activity of enzymes [68,69]. Finally, regarding the mitigating effects of AMF against salinity stress, Estrada et al. [70] concluded that AMF inoculation restricted both accumulation and uptake of Na by adjusting the expression levels of AKT2, SOS1 and SKOR genes in roots which allowed them to retain the homeostasis of K^+ and Na^+. The recent advances in omics science has also helped to reveal that microbial biostimulants' application involves great alterations in primary and secondary metabolites such as amino acids, lipids, phenolic acids and intermediates of the tricarboxylic acid (TCA) intermediates, as well as changes in protective mechanisms against stress that involve redox homeostasis, osmoregulation, stabilization of cell membranes, the production of energy through amino acid degradation and the increased expression of stress related genes [71,72].

2.3. Indirect Effects of Microbial Biostimulants

Apart from the direct effects on molecular processes, the eliciting with microbial biostimulants is associated with morphological changes such as the increase in root surface and changes in root morphology after inoculation with AMFs that both facilitate increased water and nutrient's uptake, thus helping plants to cope with the negative effects of stressors [73]. The same changes in roots have also been suggested as a mechanism of action for PGPR-based biostimulants, being regulated through hormonal activities such as indole-3-acetic acid that regulates cell elongation and division, the development of new roots and the formation of hairy roots [74]. Glick [49] also mentioned that plant growth-promoting bacteria interact with plants in different ways, such as Rhizospheric (binding to root or seed surface), Endophytic (typical in tissues inside the plant), Symbiotic (typically in root nodules), and Phyllospheric (binding to leaf or stem surfaces). Certain microbial biostimulant may protect plants against freezing and cold stress, like *Paraburkholderia phytofirmans* for grapevine, through the production of ACC [75]; *Pseudomonas fluorescens* A506 protected pear and apple trees through competition with bacteria producing INA^+; *Pseudomonas fragi*, *Pseudomonas proteolytica*, *Brevibacterium frigoritolerans*, *Pseudomonas fluorescens*, and *Pseudomonas chlororaphis* that were beneficial to bean plant through scavenging of reactive oxygen species (ROS) and inhibition of lipid peroxidation [76]; *Pantoea dispersa* 1A, *Pseudomonas* spp. and *S. marcescens* SRM that protected wheat plants via production of ACC and IAA [77]. Some microbial biostimulants can also protect crops against heat stress, such as *Pseudomonas* sp. AKMP6 and *Pseudomonas putida* AKMP7 through the reduction in reactive oxygen species (ROS), the increment in content sugar, protein, starch, proline, chlorophyll, and amino acid, and the production of phytohormones [78,79]; *Glomus* sp. protected tomato plants through the enhanced scavenging activity of ROS in the leaves and roots and the reduction in peroxidation of lipids and the production of H_2O_2 [80]; *Bacillus aryabhatthai* SRBO2 for soybean via the production of abscisic acid [81]; *Bacillus amyloliquefaciens*, and *Azospirillum brasilense* for wheat via the reduction in reactive oxygen species (ROS) and heat shock proteins pre-activation [82]; and *Paraburkholderia phytofirmans* for potato plants through the decrease in H_2O_2 and the production of ACC [83]. In apple and pear, competition with ice nucleating activity by *Pseudomonas fluorescence* A506 occurs to protect the crops from cold and frost [84]. *Burkholderia phytofirmans* strain PsJN, increased Co_2 fixation and O_2 evolution, and significantly boosted the levels of proline, phenolics and starch of the grapevine plantlets to resist cold stress [85]. Regarding water stress, Lim and Kim [86] observed that inoculation of *Bacillus licheniformis* strain K11 with pepper plants tolerated water shortage stress more effectively than un-inoculated plants, while Saia et al. [87] suggested that although different strains of AMF and *Trichoderma koningii* in greenhouse lettuce (*Lactuca sativa* L.) grown under water stress increased mineral components including Ca, Cu, Mg, P, Mn, Fe, and Zn, and different phenolic acids, the impacts of biostimulants were targeted in modulation of the biosynthesis of secondary compounds rather than improving nutrient uptake. Moreover, the inoculation of water-stressed plants with *Phoma glomerata*, *Penicillium* sp., *Exophiala* sp., *Glomus intraradices*, and *Paecilomyces formosus* may lead to greater soil exploration by roots or fungal hyphae with significantly improved root conductivity [88,89]. Finally, microbial inoculation may lead to increased hormone production such as Indole-3-acetic acid (Pseudomonas chlororaphis TSAU13 and Funneliformis mosseae) in tomato, cucumber and orange, and abscisic acid in soybean [90]. The most important protective mechanisms related to the application of various microbial biostimulants against both abiotic and biotic stresses are indicated in Table 1.

Table 1. The most important protective mechanisms related to the application of different microbial biostimulant in regards to both biotic and abiotic stresses.

Stresses	Type of Stresses	Protective Mechanisms	References
Abiotic stress			
Water stress	*Drought *Flooding	*Osmolite production *Increase in antioxidant activity *Phytohormone level modulation *Secretion of Extracellular Polymeric Substances (EPS)	[85–87]
Thermal stress	*Extreme heat *Freezing	*Emission of volatile organic compounds *Photohormone level modulation *Ice-nucleatin activity antagonism *Osmo and thermal protection *Delay of senescence	[76–79]
Nutrient stress		*Increased soil exploration *Mineral nutrients solubilization	[74,75]
Biotic stress		*Induced system resistance *Phytohormone level modulation *Direct antagonism with pathogens	[47,53–56]

3. Case Studies and Practical Application of Microbial Biostimulants on Horticultural Crops

Several paradigms of practical application of microbial biostimulants on horticultural crops indicate the significance of this innovative agronomic tool in modern agriculture that faces significant challenges from climate change and increasing world population. Maximum advantages from AMF application could be obtained by adopting useful farming practices, as AMF support plant nutrition by translocating and absorbing mineral nutrients beyond the depletion zones of plant rhizosphere and may lead to changes in secondary metabolism resulting in increased nutraceutical compounds content [91,92]. For example, a microbial-based biostimulant consisting of two strains of AMFs and *Trichoderma koningii* improved plant quality irrespective of water availability [90]. Tejada et al. [93] concluded that chlorpyrifos insecticide led to a negative influence on soil biological properties, whereas the application of biostimulants/biofertilizers reduced the toxic action of chlorpyrifos, and the low molecular weight protein of wastes increased the degradation of insecticide. Seymen et al. [94] also reported that the utilization of arbuscular mycorrhizal fungi (AMFs), and plant growth-promoting rhizobacterias (PGPRs) may improve the nutrient uptake of plants from the soil and contribute to plant development, fruit quality and final yield. AMFs and PGPRs applications may also allow plant cultivation under abiotic stress situations where cropping is inhibited or faces significant limitations [95,96]. *Aspergillus flavipes* (ATCC®16814™) may produce indole-3-acetic acid (IAA), while higher IAA levels were reached using soybean bran as culture medium for the same microbe [97]. The combined application of biostimulants including plant growth-promoting bacteria (*Bacillus licheniformis*, *Azotobacter* sp., *Bacillus megatherium*, *Azospirillum* sp., and *Herbaspirillum* sp.) and freshwater algae (*Chlorella vulgaris*) significantly influenced the plant weight of both romaine and leaf lettuce in summer and spring seasons [98]. The highest improvement in the weight of romaine lettuce (18.9%) was achieved in the spring crop, while in the case of leaf lettuce biostimulant treatment led to a 22.7% higher weight in the summer crop [97]. Colla et al. [98] also noted that the application of biostimulant products that contain *Glomus intraradices* and *Trichoderma atroviride* can promote seedlings' establishment after transplantation, as well as productivity of vegetable crops in a sustainable way. Moreover, lettuce plants grown under stress conditions, inoculated with a microbial-based biostimulant including *Rhizophagus intraradices*, and *Trichoderma atroviride*, were characterized by higher chlorophyll content and photochemical activity of PSII, and a higher nutritional status in leaf tissues [99]. Plant growth-promoting rhizobacteria (PGPR), together with humic acids applied on tomato plants, may lead to successful colonization in tomato plant roots to produce phytohormones and to solubilize soil minerals [100,101]. In the case of *Bacillus subtilis* QST 713, it was discovered that its application improved different aspects of plant growth including leaf chlorophyll content (SPAD index), the growth index, and shoot biomass of zinnia (*Zinnia elegans* "Magellan Ivory") [102].

Inoculation of *Noccaea goesingensis* with *Phomopsis columnaris* significantly increased the biomass of the Ni-hyperaccumulating plant and Ni yield per plant and stimulated different plant biometric features like dry and fresh weight and several other parameters related to leaf and root size [103]. An increase in plant biomass and yield was also recorded in peas, and Jerusalem artichoke plants, when inoculated with both PGPRs and AMFs, often showed higher biomass and yield than non-inoculated plants or plants inoculated with a single strain [104–106]. Microbial biostimulants may also offer protection against salinity stress such as *Leclercia adecarboxylata* Mo1, *Pseudomonas fluorescens* YsS6 and *Pseudomonas migulae* 8R6 in tomato [107,108], *Burkholderia* sp. and *Bacillus* sp. in pepper [109], and *Bacillus subtilis* for lettuce [110]. On the other hand, microbial biostimulants can be used for protection against drought stress, such as *Bacillus licheformis* strain K11, *Klebsiella* sp., *Achromobacter*, and *Citrobacter* sp. in pepper [111,112]; *Funneliformis mosseae* for orange [113]; and *Acinetobacter*, and *Pseudomonas* sp., *Bacillus lentus*, and *Azospirillum brasilense* for basil [114]. Specific examples of commercially available PGPR- and beneficial fungi-based plant biostimulants are FZB24®fl, Rhizovital 42® (ABiTEP GmbH, Berlin, Germany), Inomix® Biostimulant, Inomix® phosphore, and Inomix® Biofertilisant (IA B (Iabiotec), Montcada, Spain), BactoFil B10® (AGRO.bio Hungary Kft, Budapest, Hungary), Bio-Gold (BioPower, Colombo, Sri Lanka), Cedomon® (Lantmannen BioAgri AB, 756 51 Uppsala, Sweden), *Rhizosum* N Liquid PSA (Mapleton Agri Biotec Pty Limited, Mapleton, Australia), BactoFil A10® (AGRO.bio Hungary Kft, Budapest, Hungary), Micosat F® Uno; Micosat F® Cereali (CCS Aosta Srl, Quart, Italy), Bioscrop BT16 (Motivos Campestres, Mirandela, Portugal), Amase® (Lantmannen Bioagri, Uppsala, Sweden), PGA® (Organica technologies, USA), Nitroguard®, TwinN® (Mapleton Agri Biotec Pty Ltd. Mapleton, Australia), Symbion®-N, Symbion®-P, and Symbion®-K (T-Stanes & Company Ltd., Coimbatore, India), Ceres® (Biovitis, Andernos-les-Bains, France), Kodiak® (Gustafson, Inc., Plano, TX, USA), Subtilez® (BeckerUnderWood, Inc., Ames, IA, USA), Gmax® PFPR (Greenmax AgroTech, Ooty, India), Trianum-P® (Koppert, Srl, Bussolengo, Verona, Italy), Biota Max® (CusomBio, Inc., Deerfield Beach, FL, USA), and Custom GP® (CustomBio, Inc., Deerfield Beach, FL, USA) with several applications in horticultural crops [46].

3.1. Plant Growth-Promoting Rhizobacterias (PGPRs)

PGPRs may play a principal role in sustainable production of horticultural crops since they may promote germination, and also increase growth, appearance, nutritive quality and the texture of vegetables, even under arduous conditions [115]. The most important genus in this category of rhizobacteria is *Rhizobium,* which comprises 13 symbiotic, legume-nodulating species: *R. etli*, *R. galegae*, *R. gallicum*, *R. giardinii*, *R. huautlense*, *R. leguminosarum*, *R. indigoferae*, *R. hainanense*, *R. mongolense*, *R. sullae*, *R. tropici*, *R. undicola* and *R. yanglingense*; and five tumorigenic species: *R. larrymoorei*, *R. radiobacter*, *R. rhizogenes*, *R. rubi*, *R. vitis* recorded in *Agrobacterium* [116–121]. Rhizobia tolerance to soil moisture deficit may have multiple benefits for agronomic production, especially when used for seed applications under dry soil conditions [122]. Some other examples include the potential of adding *Rhizobium laguerreae* HUTR05 in non-legume crops has been beneficial, due to its capability to stimulate plant development, to alleviate saline stress impacts, and to increase plant nutritional constituent and its health potential [50]. Moreover, inoculation with PGPR strains promoted significant growth of apple (*Malus domestica* Borkh) trees in the field, since PGPR were capable of inducing indole acetic acid (IAA) and cytokinin synthesis [123,124]. Plant growth-promoting rhizobacteria (AP7 and AP18) induced systemic resistance to black rot caused by *Xanthomonas campestris* pv. *campestris* in Chinese cabbage, as well as showing a positive effect on the marketable yield of plants [125]. Similarly, seed inoculation with rhizobia significantly increased root and seed production of ahipa (*Pachyrhizus ahipa*) [126].

On the other hand, *Azospirillum* is the most thoroughly characterized plant growth-promoting rhizobacteria, which apart from fixing nitrogen as its main mode of action is phytohormone production [127]. Several reports have highlighted the positive effects of *Azospirillum* bacteria application. For example, *Azospirillum lipoferum* FK1 reduced the negative effects of salt stress on chickpea growth and performance, while *A. lipoferum* FK1 stimulated osmolytes biosynthesis, antioxidant machinery and stress-responsive genes expression under salt stress [128]. Lettuce plants inoculated with *Azospirillum* had higher product quality than control treatment at harvest even under arduous conditions, while its utilization also led to better chlorophyll content and longer storage life of treated lettuce plants grown under salt stress than control (untreated) plants [128]. *Azospirillum*-inoculated lettuce seeds also had higher germination and vegetative growth than non-inoculated ones after being subjected to NaCl stress [129]. Rodrigues et al. [130] reported that *Azosipirillum* sp. UENF-412522 is a good candidate for bioinoculant formulations focused on plant growth promotion in sustainable systems. Moreover, *Azospirillum* strains OAD-2 and OAD-11 increased plant growth and yield parameters and played an important role in N nutrition of blanket flower (*Gaillardia pulchella*) [131]. Inoculation of coriander seeds via dual culture of *Azospirillum brasilense* and *Azotobacter chroococcum* increased grain yield, and also stem fresh and dry weights by 11.6, 11.3, and 17.2%, respectively, while it also enhanced total plant fresh and dry weights by 6.1 and 10.2%, respectively, as compared to control seeds [132]. Moreover, inoculation with *Azotobacter chroococcum* and *Azospirillum brasilense* was effective in improving pennyroyal physiological and phytochemical parameters, while the highest ABA, proteins, soluble sugars, phenolic, flavonoid and oxygenated monoterpenes contents, as well as DPPH radical scavenging activity, were observed in the inoculated pennyroyal (*Mentha pulegium* L.) plants under severe drought stress [133].

Plant growth promotion activities of *Azotobacter* are related to growth hormone production, siderophore production, and nitrogen fixation, as well as to its bioremediation potential like oil-contamination removal, heavy metal tolerance, and pesticide degradation [134]. Moreover, increasing the quality and productivity of black cumin (*Nigella sativa*) by using *Azotobacter* as N_2 biofertilizer is also reported [135]. *Azotobacter salinestris* tolerated high contents of metal-oxide nanoparticles (NPs), and bacterial inoculation increased photosynthesis, flower formation, numbers of fruit, and lycopene content in tomato plants [136]. Kumar et al. [137] also suggested the application of *Azotobacter chroococcum* had also notable impacts in yam (*Dioscorea alata* L.) under nutrients deprivation, while it enhanced the biochemical properties of the final product. On the other hand, *Azotobacter chroococcum* and *Azotobacter vinelandii* showed great potential to diminish the negative effects of drought stress in eggplant (*Solanum melongena* L.), since they supported the stress tolerance of the plant by mitigating the drought-related oxidative damage [138]. Moreover, combined application of *Azotobacter chroococcum* and indigenously isolated strains of AMF species from local litchi for air-layering resulted in better adaptation to specific agroclimatic and ecological zone conditions [139]. Both *Azotobacter* and AMF bioinoculants significantly enhanced survival percentage of saplings from 25% to 50% under salt stress, and increased all growth parameters and microbial count in the rhizosphere of mulberry (*Morus alba*) plants [140]. Similarly, inoculation of *Azotobacter chroococcum* and AMF species positively influenced desirable saplings' growth parameters for early grafting of apple grown under solarized black plastic mulching [141]. In addition, *Azotobacter chroococcum* CL13 significantly enhanced leaf numbers, stem height, and stem and rhizome fresh biomass as well as the pharmaceutically important curcumin content in *Curcuma longa* L. [142].

Two plant growth-promoting rhizobacteria separated from the rhizosphere of *Prunus domestica* were recognized as *Pseudomonas stutzeri* and *Bacillus toyonensis*, and improved tomato plant growth under salt stress, while they increased the establishment of *Vitis vinifera* and peach root stock GF305 when transferred from in vitro conditions to the greenhouse [143]. The inoculation with isolated Cd- and Pb-resistant PGPR of *Bacillus* sp. QX8 and QX13 from heavy-metal-contaminated soil, remarkably, stimulated the growth of *Solanum nigrum* and improved Pb and Cd phytoextraction [144]. PGPR application also increased the mineral nutrition of onion plants that recorded the maximum mineral content in bulb and leaves [145]. The PGPR application was effective only in reducing the nitrate content of basil leaves, whereas plants were negatively influenced by a high percentage of organic liquid fertilizer [145]. Indigenous plant growth-promoting bacteria colonized roots of avocado trees at high cell densities, and they could confer increased tolerance to environmental and salinity stress [146].

Seed inoculation with *Bacillus* species showed a beneficial trend in growth characteristics and nutrient status of cucumber (*Cucumis sativus* L.) plants grown under high salinity, although not as pronounced as in the case of Si application [147]. The use of rhizobacteria under water stress also improved the antioxidant and photosynthetic pigments in basil plants, while *Pseudomonas* sp., in particular, significantly increased the CAT enzyme activity [148,149]. PGPR consortium accumulated more AsIII in leaves but induced plant defense mechanisms by reducing most of AsIII toxic effects in grapevine (*Vitis vinifera* L.) [150]. Grapevine inoculation with PGPR (*Bacillus licheniformis*, *Micrococcus luteus*, and *Pseudomonas fluorescens*) in As(III) stress conditions increased antioxidant activity, and also showed a significant decrease in $NaAsO_2$ toxic effects in in vitro grapevine plants inoculated with *M. luteus*, suggesting that this bacterium is a good candidate for bioremediation towards As(III) contamination [150].

Apart from single bacterium formulations, co-inoculation with more than one bacterial strain has also found practical application with beneficial effects on plant growth and yield and quality parameters of crops [150–153]. Inoculation with *Bacillus amyloliquefaciens* resulted in maximum enhancement of seed germination (84.75%) and seedling vigor (1423.8), along with an increase in vegetative growth parameters of chilli (*Capsicum annum* L.) [152]. For example, utilization of *Pseudomonas* BA-8 and *Bacillus* OSU-142, in combination or alone, had a notable effect on yield, growth and nutritional status of sweet cherry plant (*Prunus avium* L.) [154]. Co-inoculation of BA-8 + OSU-142 escalated Zn and Fe contents of leaves up to 50.5% and 35.5% compared to the control treatment, respectively [152]. Moreover, co-inoculation of *Pseudomonas* R62 and R81 (PGPR) with *Glomus intraradices* (AM fungi) decreased the mortality and boosted the growth of the litchi air-layers, the leaf macro- (N, P, and K), and micronutrients (Zn, Cu, and Fe) [152]. The combined application *Pseudomonas putida* and *Azotobacter chroococcum* showed no effect on disease control of cumin (*Cuminum cyminum* L.) [153]. *Bacillus* M3 and *Microbacterium* FS01 applied in combination showed a high potential to increase the yield, growth and nutrition of apple trees [154]. PGPR strains (ISE14 and CCR80) increased total microbial activities in pepper (*Capsicum annuum* L.) rhizosphere in the soil [155]. PGPR strains such as *Pseudomonas fluorescens*, *Bacillus subtilis*, *Sinorhizobium meliloti*, and *Bradyrhizobium* sp. induced significant increases in shoot length, shoot weight, number of leaves, number of nodes, and root dry weight in sweet marjoram (*Origanum majorana* L.) plants [156], while the application of PGPR formulations (*Pseudomonas aeruginosa* MML2424 and *Bacillus subtilis* MML2490) also increased turmeric rhizome yield and exhibited multiple biocontrol mechanisms against fungal pathogens (*Rhizoctonia solani* MML4001, *Fusarium solani* MML4002, *Schizophyllum commune* MML4003, *Macrophomina phaseolina* MML4004, *Fusarium graminearum* MML400, *Fusarium solani* MML4006, and *Fusarium solani* MML4007) [157]. Moreover, the *ad planta Bacillus cereus* and *Pseudomonas putida* decreased bacterial wilt in tomato genotypes [158]. PGPR species (*Pseudomonas fluorescens* WCS417 and *Bacillus amyloliquefaciens* GB03) could mitigate the adverse consequences of drought stress, and offered a sustainable means of increasing the tolerance of peppermint (*Mentha piperita*) plants grown under water deficit conditions [159]. Moreover, inoculation reduced the amount of proline and membrane lipid peroxidation under the different stressed conditions tested [159–162]. The most important effects of plant growth-promoting plant growth rhizobactier on different horticultural plants are shown in Table 2.

Table 2. The most important effects of PGPR on horticultural plants.

Types	Plant	Effects	Reference
Azotobacter	Eggplant (*Solanum melongena* L.)	**Azotobacter chroococcum* and *Azotobacter vinelandii* rhizobacteria species have the potential to decrease the adverse impacts of droughts stress by mitigating the drought-related oxidative damage.	[138]
	Tomato (*Solanum lycopersicum* L.)	**Azotobacter salinestris* strain could be an alternative tool to boost the production of tomato.	[136]
	Litchi (*Litchi chinensis* Sonn.)	**Azotobacter chroococcum* strains can be applied for air-layering for better adaptation in different conditions.	[139]
Arthrobacter	Strawberry (*Fragaria × ananassa*)	**Arthrobacter agilis* UMCV2 can be inoculated in micropropagated strawberry plants and increase the yield and fruit quality under greenhouse conditions.	[160]
Azospirillum	Lettuce (*Lactuca sativa*)	*Seed inoculation with *Azospirillum* could increase product quality and improve storage life in lettuce grown under salt stress.	[163]
Bacillus	Tomato (*Solanum lycopersicum* L.)	**Bacillus licheniformis* NJ04 may increase root length and shoot length of treated plants.	[161]
	Tomato (*Solanum lycopersicum* L.)	**Bacillus velezensis* 83 can be used for biological control of five different genera of phytopathogenic fungi, namely, *Botrytis*, *Sphaerotheca*, *Leveillula*, *Erysiphe*, and *Colletotrichum*.	[162]
	Lettuce (*Lactuca sativa*)	*Low concentrations of *Bacillus* sp. BCT9 improved length and lateral root.	[163]
***Enterobacter* sp.**	Tomato (*Solanum lycopersicum* L.)	*The Xy3 strain of *Enterobacter* sp. had notable controlling effects against bacterial wilt (*Ralstonia solanacearum*).	[164]
Burkholderia	Tomato (*Solanum lycopersicum* L.)	**Burkholderia cenocepacia* ETR-B22 volatiles suppressed *Botrytis cinerea* infection. *Microbial volatile organic compounds of *Burkholderia cenocepacia* ETR-B22 could be used as an important biofumigant for extending postharvest tomato fruit shell life and controlling grey mold disease.	[165]
	Tomato (*Solanum lycopersicum* L.)	**Burkholderia* sp. strain N3 improved tomato seedling height, dry weight, and nutrient uptake. *It can promote Fe^{3+} uptake, while Zn^{2+} absorption accompanied Cd accumulation. **Burkholderia* sp. strain N3 facilitated gene expression and alleviated Cd toxicity in tomato plants.	[166]

3.2. Arbuscular Mycorrhizal Fungi (AMFs)

Mycorrhizas are a symbiotic association between fungi and plant roots, which are present in several forms according to both fungal taxonomy and host plant. Two important parameters that influence the distribution of these forms are the climatic and soil conditions and the host plant distribution [167,168]. They can significantly boost the efficiency of mineral absorption, while they appear in two major categories such as endotrophic and ectotrophic [169]. Recently, microbial stimulants such as arbuscular mycorrhizal fungi (AMFs), which often live in the rhizosphere, have been among the topics that are consistently studied in vegetable production within the context of sustainable agriculture, since they can increase plant nutrient uptake and contribute to plant development, yield and final product quality, while showing considerable effects in the suppression of phytopathogens.

The main types of AMF related to the sub-phylum Glomeromycotina of the phylum Mucoromycota [170], and four orders of AMF, specifically, *Glomerales*, *Paraglomerales*, *Archaeosporales*, and *Diversisporales*, have been recognized in this sub-phylum that also contains 25 genera [171]. Recent research reports studied the role of AMF in promoting the vegetative and reproductive growth, yield quality, stress physiology, and disease resistance of horticultural plants (fruit trees, vegetables, flower crops, and ornamental plants) [172]. AMF improved the nutrient and water supply of horticultural plants, increased their yield and quality, and enhanced their tolerance of environmental stress and resistance to pathogens [173]. AMF indirectly affects macropores' features by mediating root chemical traits [174]. AMF also play an important role in soil nitrogen cycling, and it has been reported that AMF significantly decreased soil N_2O emission and increased microbial biomass nitrogen and plant biomass compared to the non-AMF treatment [175].

Several examples of the positive effects of AMF application on horticultural crops have been reported so far. For example, mycorrhiza Y-037 has powerful infection intensity and markedly stimulated plant growth of Guizhou blueberry [175]. Fungal inoculations partly increased fruit quality and mineral element constituents, depending on the fungi species, while the cultured mycorrhiza-like fungus *Piriformospora indica* relatively replaced AMF in applications on citrus plants [176]. Similarly, inoculation of coarse mint with AMF *Rhizophagus clarus* and a high dose of P boosted plant growth and the essential oil yield, while it increased carvacrol content [177]. Moreover, the inoculation of AMFs provided outstanding dry weight gain in lemon balm (*Melissa officinalis* L.), and significantly contributed to high essential oil yield [178]. The mixed AMF inoculation in chamomile cultivation increased both plant productivity and quality of flower heads, particularly regarding its content of phenolic compounds [179]. AMF inoculation had positive influence on the yield of raspberry (*Rubus idaeus* L.) [180], while the combined implementation of biochar with AMF increased the colonization potential of AMF and significantly improved the photosynthetic potential of *Tamarindus indica* by boosting the contents of carotenoids and chlorophyll [181]. Similarly, dual application of biochar and AMF was more beneficial to increasing plant growth, root morphological characteristics and chlorophyll content in okra, compared to other treatments [182]. Two mycorrhizal fungi, *Gigaspora gigantean* (Gg) and *Glomus mosseae* (Gm), affected plant growth indirectly, and in some situations they reduced the inputs of chemical pesticides in eggplant [183]. The utilization of AMF and moderate fertilization in a low P soil with low-to-medium mycorrhizal potential may also have a positive influence on tomato plants through the optimization of biomass yield and production [184]. AMF can also boost the bioavailability of P in the rhizosphere and significantly increase the N-utilization in inoculated onion plants [185]. Finally, various species of filamentous endophytic fungi, such as *Trichoderma*, are capable of controlling the pathogens *Xylella fastidiosa* and *Pseudomonas savastanoi* through the production and release of secondary metabolites, while they are also effective against *Colletotrichum* sp. and *Oomycetes* sp. [186].

Moreover, the mycorrhiza (*Glomus mossea*) and growth-promoting bacteria (*Azospirillum*) resulted in the highest yields, total carotenoids, and chlorophyll in fennel plants subjected to water deficit stress [187]. A dual utilization of AMF and/or vermicompost increased water uptake and decreased drought damage in cactus (*Opuntia ficus-indica*), while it also lessened the oxidative stress markers [188]. Under limited irrigation, AMF strains increased growth of tomato plants regardless of irrigation status, and they also restored shoot and root dry weight [189]. Moreover, AMF colonization ameliorated the osmotic adjustment originating not from proline but from non-structural carbohydrates (NSC), Ca^{2+}, K^{+}, and Mg^{2+}, resulting in the improvement in drought tolerance in the leaves of citrus [190]. The colonization of olive roots by *Rhizophagus irregularis* DAOM 197,198 significantly reduced the deleterious effect of water deficit stress by up-regulating the primary and secondary metabolism and preserving a high stem water potential level in olive plants (*Olea europaea*) [191]. AMF may improve the response of plants to irrigation with treated waste-water and decrease the cost associated with using other water sources in Nemesia production (*Nemesia* × *hybridus*) [192], pepper (*Capsicum annuum* L.) [193], and pomegranate (*Punica granatum* L.) plantlets [194]. AMFs can also alleviate the detrimental impacts of salinity on *Ligustrum vicaryi* plants through the increase in N, Ca^{2+}, Zn^{2+}, Mg^{2+} and soluble proteins content [195], while they may affect the palmarosa (*Cymbopogon maritinii* (Roxb.) Wats. Var. Motia Burk) seedlings' emergence and growth under salinity conditions, while *Rhizophagus intraradices* is beneficial to healthy and significant seedlings' emergence [196]. The mycorrhizal-treated *Vitis vinifera* L. plants obtained by tissue culture showed better physiological and nutritional status and had higher relative water content (RWC) and photosynthetic rate during hardening [197]. Inoculation with *F. mosseae* and *R. intraradices* increased essential oil production in *Thymus daenensis* and *T. vulgaris* L., especially under water stress conditions, which significantly reduced essential oil biosynthesis; therefore, AMF inoculation could be suggested as an excellent strategy to alleviate the adverse effects of water stress and to allow cultivation under limited water conditions [198]. On the other hand, AMF symbiosis did not impact corm growth (diameter and weight), but increased the production of replacement corms of saffron (*Crocus sativus* L.) plants while it diminished the incident of fungal diseases (ca. −72%) compared to control conditions [199]. *Rhizophagus intraradices* inoculation increased productivity of *Ocimum tenuiflorum* and boosted the quality of the final products [200]. In addition, AMF inoculation improved pepper growth both under salt or control (no salt addition) conditions, and decreased cell membrane leakage [201]. Similarly, pre-inoculation of tomato transplants with AMF upgraded yield and helped to reduce disadvantageous impacts of salt stress on crop yield [202]. The combined application of GA_3 (Gibberellic acid) and AMF (*Rhizophagus irregularis*) reduced growth impairment under salinity conditions by adjusting the hormonal balance of plants [203]. The application of AMFs was able to boost the productivity of sweet basil (*Ocimium basilicum*) plants under salinity conditions, and mycorrhizal inoculation notably increased water use efficiency and chlorophyll content under salinity stress [204]. AMF and dopamine significantly increased root length, surface area, average diameter, and number of root forks of apples (*Malus domestica* Borkh.), which increased the surface area in contact with soil nutrients and water under salt stress [205].

AMF formation significantly increased the high temperature tolerance of lettuce, a finding that could be attributed to PSII system protection from damage under high temperature [206]. In addition, it has been suggested that the mycorrhizal symbiosis reduced the Na^+ and Cl^- contents and increased the relative water content (RWC), the total fresh and dry weight, and the photosynthetic activity of olive plants [207]. AMF symbiosis increased the Ca^{2+} content in peanut plants, while Ca^{2+} participated in AMF symbiosis signaling through the Ca^{2+} signal transduction pathway which plays a significant function in protecting plants against stresses [208]. Moreover, AMF application suppressed plant Cd absorption, and biochar addition further inhibited root Cd concentration following the AMF inoculation while the combined use of AMF and biochar decreased Cd toxicity in chicory plants (*Cichorium intybus* L.) [209]. The AMF consortium (*Glomus* spp. and *Acaulospora* spp.) could inhibit *Fusarium* wilt of cucumber and, consequently, showed promising results as a biological control factor in greenhouse agro-ecosystems [210]. The mycorrhizal inoculation (*Glomus intraradices*) showed an important part in the attenuation of the impacts of sulfates contained in gypsum substrate on olive trees [211]. AMF affected positively polyphenolic compounds and antimicrobial activity of *Tamarix gallica*, while AMF colonization of roots had a positive effect on flavones and flavonols production [212]. *Rhizophagus intraradices* and *Funneliformis mosseae* considerably promoted root proline and total soluble sugars and total phenolics in shoots and roots versus non-mycorrhizal treated valerian (*Valeriana officinalis* L.) plants [213]. The mango (*Mangifera indica* L.) root stocks responded to AMF inoculation in the nursery and also in the field, by showing improved plant growth, nutrient uptake and yield [214]. The most important effects of AMF on different horticultural plants are shown in Table 3.

Table 3. The most important effects of AMF on horticultural plants.

Types	Plant	Effects	Reference
Arbuscular mycorrhizal fungi (AMF)	Bishop's flower (*Ammi majus*)	*Its application can induce accumulation of phyto-molecules, coumarin, which might improve its medicinal and pharmacological applications.	[215]
	Black cumin (*Nigella sativa* Linn.)	*The colonization can increase relative water content (RWC), Chl b content, and micronutrient uptake.	[216]
	Cacao (*Theobroma cacao* L.)	*It can improve the overall growth and can positively increase the yield of cacao plants in acidic soils.	[217]
Glomus tortuosum	Chicory (*Cichorium intybus* L.)	*AMF, biochar and N fertilizer applications enhanced chicory biomass.*AMF and biochar applications increased nutrient absorption, and reduced Cd absorption.	[209]
Funneliformis mosseae	Cucumber (*Cucumis sativus* L.)	*The enhanced secondary metabolism and integrated transcriptional regulation might play a crucial role in AMF-mediated alleviation of chilling stress in plants.	[218]

Table 3. *Cont.*

Types	Plant	Effects	Reference
Pervetustus simplex, *Claroideoglomus etunicatum*, *Albahypha drummondii*, *Septoglomus xanthium*, *Funneliformis mosseae*, and *Rhizoglomus irregulare*	Date palm (*Phoenix dactylifera* L.)	*Shoot length, and stem diameter were significantly higher in treatments augmented with compost and AMF.	[219]
Claroideoglomus etunicatum, *Rhizoglomus irregulare*, *Diversispora versiformis*	Eggplant (*Solanum melongena* L.)	*The inoculation is an effective strategy for alleviating cold stress.	[220]
Glomus intraradices	Fig (*Ficus carica* L.)	*Plants positively responded to the mycorrhizal inoculation, and AMF induced different root architecture models.	[221]
Glomus deserticola, *Gigaspora margarita*	Olive (*Olea europaea* L.)	*Mycorrhizal symbiosis decreased the Na^+ and Cl^- contents, and improved the RWC, the total fresh and dry weights and the photosynthetic activity.	[222]
Rhizophagus irregularis		*The inoculation exhibited better performance under drought, especially under partial-root zone drying (PRD) treatment.*The combination of 50% deficit irrigation and AMF could cause the resistance of olive to drought.	[222]
Funneliformis mosseae, *Funneliformis constrictum*,	Onion (*Allium cepa* L.)	*Application of AMF and *Trichoderma viride*, for onion plants assists their growth in nutrient-deficient soils amended with fish waste.	[223]
Gigaspora margarita, and *Rhizophagus irregularis*	Pistachio (*Pistacia vera*)	*The use of composted materials improved its seedling´s response to native AMF under drought conditions.	[224]
Glomus mosseae, *Acaulospora laevis*, *Glomus manihotis*, and a mixed AMF strain	Pomegranate (*Punica granatum* L.)	*Growth, physiological, and bio-chemical activities were effectively improved by bio-hardening.	[194]
Cetraspora pellucida, *Claroideoglomus etunicatum*	Strawberry (*Fragaria* × *ananassa* Duch.)	*Plants grown with 9% of biochar and inoculated with *C. etunicatum* showed more profuse root system.	[225]
Rhizophagus fasciculatus, *Rhizophagus aggregatus*, *Rhizophagus irregularis*	Tangerine orchard (*Citrus reticulata* L.)	*Inoculation had positive effect on final yield.	[226]

4. Future Remarks and Conclusions

Microbial-based biostimulant products are expected to be regularly used by farmers in the near future, as soon as the industry supplies products with high quality and reliable inoculants. Some of the positive impacts of these products include the amelioration of nutrient intake, the improvement in the photosynthesis process, the regulation of plant hormones biosynthesis, the boost of plant tolerance to abiotic stress, and the increase in crop quality and yield. Therefore, microbial biostimulants can significantly improve sustainable agricultural production by boosting plant tolerance to abiotic stress, improving uptake and effective use of nutrients, increasing crop quality and harvestable yields, and improving soil health, while they can contribute to biocontrol of pest and pathogens of crops and help reducing chemical inputs.

The market for plant biostimulants is rapidly increasing with new products becoming available for more crops, while their use is becoming a common practice in most farming systems. Since microbial biostimulants are considered important tools for crop production with tremendous benefits, the new regulations should be formed according to the most updated scientific evidence, focusing on farmers and market requirements for safe and healthy products. However, although the development and progress of the respective scientific sector shows increasing trends, several challenges considering the interaction of biostimulant products with plant species and the phenological stage of horticultural crops as well as environmental conditions during biostimulant application need further research. Revealing the mechanisms behind these effects will help to achieve reproducible results and allow the extrapolation of experimental observations to commercial conditions and to real-life cropping systems, while it will consolidate microbial biostimulant application in farmers’ quiver for coping with modern challenges related to climate change and food insecurity due to increasing global population. Therefore, the study of the molecular mechanisms through omics sciences is needed to reveal the key actions associated with the observed beneficial effects on plants. Moreover, the spectrum of microbes with agricultural applications needs to be broader with more non-phytopathogenic and non-toxigenic species, focusing on stress alleviation parameters as well as tolerance to abiotic and biotic stressors, while combined applications with consortia of PGPRs and/or AMFs should be considered and further tested in field conditions to identify synergistic positive effects on crops. Finally, conventional practices that lead to land and biodiversity degradation should be redesigned, and novel practices such as biostimulants application should be integrated in new farming systems.

In conclusion, the utilization of microbial biostimulants is not only an environmentally friendly practice and promising method, but it may also lead to improved use efficiency of natural resources via water-deficit irrigation techniques, to reduced agrochemical inputs such as pesticides, mineral fertilizers and other agrochemicals, and to reclamation of arable land that is not appropriate for conventional farming.

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Abbreviations

PGBP: Plant growth-promoting bacteria; AMF: Arbuscular mycorrhizal fungi; MLE: Moringa leaf extract; ACC: 1-Aminocyclopropane-1-carboxylic acid; ROS: Reactice oxygen species; IAA: Indole-3-acetic acid; Gd: *Gigaspora gigantean*; Gm: *Glomus mosseae*; NPs: Nanoparticles; GA_3: Gibberellic acid; RWC: Relative water content; PRD: Partial-root zone drying; SWC: Swine wastewater compost.

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