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# Advancing sustainable agriculture: The role of biostimulants in crop production with emphasis on medicinal and aromatic plants

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**ABSTRACT**

Biostimulants are gradually being accepted as major elements of sustainable agriculture, which help to stimulate and promote agricultural productivity and defenses by altering physiological and biochemical conditions instead of providing direct nutrients. This review discusses the action of the key classes of biostimulants, comprising seaweed extracts, humic substances, protein hydrolysates, microbial inoculants, and chitosan, and how they enhance nutrient uptake, stress tolerance, and biosynthesis of secondary metabolites. A special focus is made on medicinal and aromatic plants (MAPs), in which the response of bioactive compounds to biostimulants is greatly improved in terms of biomass, essential oils, and bioactive chemicals directly affecting the quality of market and therapeutic value. The utilization of cutting-edge molecular technologies, such as next-generation sequencing and metabolomics, is mentioned to understand the interaction between plants and microbes and enhance the formulation of biostimulants and prospects to utilize agro-industrial residues within a circular bioeconomy framework. Although the global market is rapidly expanding, there are still some issues associated with standardization, dosage optimization, and harmonization of the regulations. On the whole, biostimulants represent a scientifically promising strategy for sustainable crop production, enhanced phytochemical quality in MAPs, and ecologically sound agricultural intensification.

## 1. INTRODUCTION

Medicinal and aromatic plants (MAPs) are economically important crops widely used in pharmaceuticals, traditional medicine, nutraceuticals, cosmetics, perfumery, and food industries [1,2]. Recent analysis of the International Trade Centre trade data reported that global MAP exports reached approximately US$4.18 billion in 2023, with China and India among the leading exporters; India accounted for 10.54% of global MAP export value in 2023. India also has a substantial domestic medicinal-plant sector and an established export trade, with government estimates documenting significant volumes of medicinal-plant and herbal raw-drug trade. Major Indian MAP export commodities include psyllium, turmeric, senna, and zedoary [3–6].

MAP cultivation has been constrained by a number of challenges despite its growing demand, such as climate fluctuations, soil degradation, pest and disease pressure, and overexploitation of natural resources. These stresses harm plant productivity and the accumulation of secondary metabolites, which are of medicinal and commercial value [7,8]. This means that methods are needed that are more sustainable in terms of maintaining ecological balance but at the same time improving crop performance.

Biostimulants are thus emerging as a promising alternative pathway, which can overcome these limits and also facilitate sustainable cultivation. Under some circumstances, Biostimulants are chemical, biological, or environmental substances that trigger responses in the plant and enhance the efficiency of nutrient assimilation, the plant's ability to withstand stress, crop yield, and crop quality [9,10]. A few reports suggest that rooting system growth, biomass increase, productivity of essential oils, and levels of bioactive metabolites such as phenolics, terpenoids, and alkaloids might be improved by biostimulant application in MAPs [11–13]. However, they do not work well on every crop, environmental condition, product type, application rate, or application method [9,14–18]. Field-level validation has been limited, and inconsistent results are often experienced from different soil, climate, and management interactions that occur in the field, though responses are often reported under controlled conditions [18–21].

## 2. METHODOLOGY

A structured literature survey was conducted to review the various MAPs, and a balanced and comprehensive evaluation of biostimulants

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was performed. The following measurements were highlighted as being prone to variability among field responses, differences in formulation, and shortfalls in the ability to do long-term validation. The literature was systematically compiled and critically analyzed from 2012 to 2026.

### 2.1. Literature Search Strategy

Major scientific databases such as Scopus, Web of Science, Science Direct, Springer Link, Taylor & Francis Online, and Frontiers were used to retrieve literature. Information used in the design of supplementary data was obtained from authoritative institutional reports and technical publications.

The plant biostimulants (PBs) OR biostimulants were combined with medicinal plants OR medical and aromatic plants OR medical and aromatic crops by applying the Boolean operator (AND) in the search strategy. Searches were also conducted for crops, including *Mentha piperita*, *Withania somnifera*, and *Ocimum basilicum*.

### 2.2. Inclusion and Exclusion Criteria

Studies were included if they: (i) investigated PBs in MAP systems; (ii) reported agronomic, physiological, biochemical, or quality-related responses; (iii) contained clear experimental methodology and replication; and (iv) were published in peer-reviewed journals or recognized institutional reports.

Studies were excluded if they: (i) lacked sufficient methodological details or statistical analysis; (ii) were anecdotal or non-scientific reports; or (iii) focused exclusively on non-MAP crops without relevant mechanistic insights.

The literature was screened for topical relevance based on titles, abstracts, and, where appropriate, full-text examination. As this study was designed as a structured narrative review rather than a formal systematic review, no PRISMA-style quantitative screening process or pooled analysis was performed. Relevant studies were synthesized thematically according to biostimulant type, MAP species, application conditions, and reported agronomic, physiological, biochemical, molecular, and phytochemical responses.

### 2.3. Data Extraction and Thematic Classification

Data gathered from selected studies comprised: crop species, type of biostimulant, application condition, dosage, environmental condition, and main outcomes. The literature was then sorted out into thematic groups regarding the following: (a) plant growth and plant productivity, (b) tolerance to abiotic stress, (c) nutrient-use efficiency, (d) secondary metabolite and quality enhancement, and (e) physiological and molecular mechanisms.

### 2.4. Quality Assessment

Studies were judged based on the following methodology: experimental design, replication, statistical analysis, and clarity of treatment description. An increased focus was put on field-validated studies, multi-seasonal studies and experiments under varying agro-climatic situations towards enhancing the greater applicability and reliability of results.

## 3. RECENT TRENDS IN BIOSTIMULANTS

The use of biostimulants in climate-smart and sustainable agriculture is increasingly being assessed, particularly in protected environments for high-value crops. Mechanistic studies in recent years have shed light on the possible molecular, physiological and rhizospheric activities of biostimulants. A range of products, such as protein hydrolysates, microbial inoculants, and seaweed extracts, have been suggested by transcriptomic and metabolomic studies to affect phytohormone signaling, antioxidant responses, and nutrient uptake pathways, which could result in increased stress tolerance under certain conditions [9,19].

The regulatory developments in the past few years have helped standardize the industry and provide a scientific basis for assessing the use of biostimulants. The EU Fertilising Products Regulation (EU 2019/1009) established biostimulants under a harmonized legal framework, differentiating them from fertilizers and pesticides, and requires that any stated product effects (e.g., improved nutrient-use efficiency, enhanced tolerance to abiotic stress, or quality traits) be supported by scientifically validated evidence [22,23].

Another trend is technological innovation. The developments in microbial consortia, encapsulation technology, nano-formulations, as well as precision-agriculture tools, have enhanced precision delivery and increased bioactivity duration. Integration with digital agriculture systems may support more targeted application strategies based on crop and environmental conditions, although field-level performance remains variable [24].

### 3.1. Categories of Biostimulants

Biostimulants refer to the wide category of compounds and microorganisms that have been applied to promote growth, stress resistance, and quality of crops by different biochemical and physiological pathways [20,25]. Understanding these categories is essential for aligning PB use with specific crop requirements, environmental conditions, and production objectives. The principal categories are outlined below.

#### *3.1.1. Seaweed extracts*

Bioactive compounds: betaines and phytohormones (cytokinins and auxins) are found in seaweed extracts, predominantly from brown macroalgae such as *A. nodosum* [26]. These compounds enhance cell division and nutrient uptake and tolerance to drought, salinity, and temperature stress by balancing antioxidant systems and changing osmotic balance by promoting root growth [27].

#### *3.1.2. Humic substances*

Humic substances, including humic acids, fulvic acids and humins, are products of the decomposition and transformation of plant and microorganism-derived organic matter. They can improve micronutrient availability through complexation and chelation and influence root physiological processes, including plasma-membrane $H^+$-ATPase activity, thereby facilitating nutrient uptake [28]. In addition, humic substances may improve soil structure, water retention, and biological activity, thereby supporting root development and soil health [29]. Crop-specific experimental evidence further indicates that humic acid application can improve biomass production and essential-oil-related traits in MAPs such as *Origanum vulgare* [30].

#### *3.1.3. Protein hydrolysates and amino acids*

Due to the enzymatic hydrolysis of protein-rich feedstocks, protein hydrolysates comprise bioactive peptides and amino acids that can stimulate plant metabolic processes and enhance tolerance to abiotic stress [9,20]. Proline and glutamate are important amino acids

involved in osmotic adjustment, nitrogen metabolism, and redox regulation. Their exogenous application or presence in amino-acid-based biostimulants has been associated with improved physiological performance, nutrient assimilation, and plant growth under stress conditions [12,31].

#### *3.1.4. Microbial inoculants*

Microbial inoculants including nitrogen-fixing bacteria (e.g., *Rhizobium* spp.), arbuscular mycorrhizal fungi (AMF), and plant-growth-promoting rhizobacteria (PGPR) enhance root architecture, improve phosphorus and nitrogen acquisition, and induce systemic resistance to pathogens [21,32]. They establish positive symbioses that enhance nutrient exchange and resiliency to stress in low-input systems [18].

#### *3.1.5. Chitosan and other elicitors*

Chitosan and other biopolymers can induce molecular responses and enhance plant stress tolerance through changes in gene expression [33,35]. Specific oligosaccharides and microbial metabolites are other elicitors that induce systemic acquired resistance and enhance the quality of crops by imitating pathogen-associated molecular patterns [35].

### 3.2. Mechanisms of Action

Biostimulants enhance crop performance by regulating vital physiological and metabolic mechanisms that enhance crop growth, nutrient-use efficiency, and stress tolerance, rather than by directly supplying nutrients or acting as pesticides. Their effects arise from the interaction of multiple regulatory pathways [9,36] (Fig. 1).

#### *3.2.1. Enhancement of photosynthesis*

Biostimulants have been shown to increase chlorophyll content and activate photosynthetic enzymes, leading to enhanced carbon assimilation and biomass accumulation. For example, such effects have been reported in lettuce (*Lactuca sativa*) and basil (*O. basilicum*) [19,20].

#### *3.2.2. Activation of antioxidant systems*

Under abiotic stress conditions, biostimulants enhance the activity and expression of antioxidant enzymes such as superoxide dismutase, catalase, and peroxidases, thereby maintaining cellular redox homeostasis [37]. These effects have been reported in crops such as pepper (*Capsicum annuum*), maize (*Zea mays*), and rosemary (*Rosmarinus officinalis*) [38–40].

#### *3.2.3. Improved water-use efficiency*

Biostimulants have a beneficial effect on root architecture, hydraulic conductivity, and osmotic regulation, resulting in better stomatal control and drought tolerance [41]. These effects have been reported in wheat (*Triticum aestivum*), maize (*Zea mays*), and peppermint (*Mentha* × *piperita*) [18,38,42].

#### *3.2.4. Rhizosphere modulation and nutrient acquisition*

They can influence root exudation and beneficial plant–microbe interactions, thereby promoting rhizosphere processes involved in nutrient mobilization and acquisition [43,44]. Microbial biostimulants have also been shown to improve phosphorus availability and acquisition in onion (*Allium cepa*) through phosphate-solubilizing

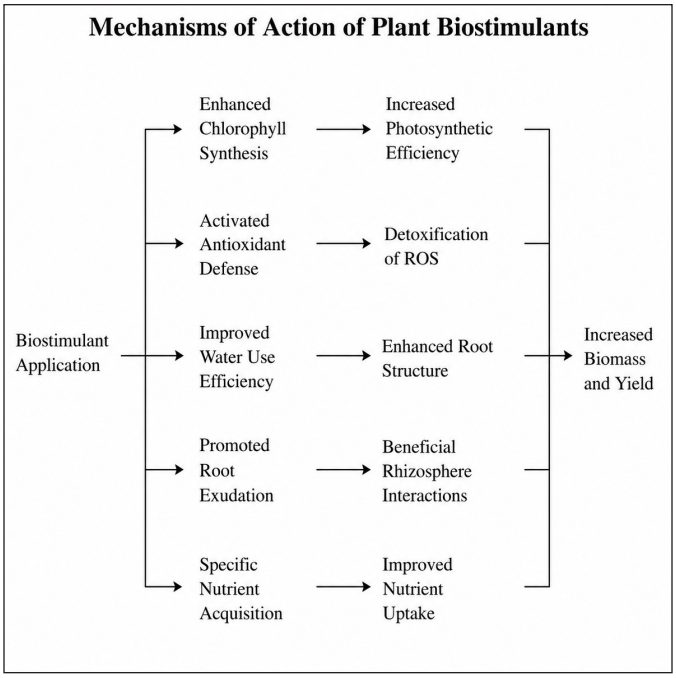


**Figure 1.** Biostimulants improve plant growth by stimulating physiological and biochemical processes, including enhanced chlorophyll synthesis, antioxidant defense, water-use efficiency, root exudation, and nutrient acquisition. These responses collectively enhance photosynthetic efficiency, ROS detoxification, root architecture, rhizosphere interactions, and nutrient uptake, thereby increasing biomass accumulation and yield.

microorganisms [45]. Similar plant-growth-promoting effects have been reported in MAPs, including thyme (*Thymus vulgaris*), following inoculation with beneficial microorganisms [46].

These mechanistic insights are valuable, though they have predominantly been established under controlled conditions and cannot always be reliably reproduced across diverse field environments.

### 3.3. Diversification of Sources and Actives

In recent years, the biostimulant portfolio has expanded considerably beyond established categories such as seaweed extracts, humic substances, and protein hydrolysates. The novel compounds now emerging include postbiotic metabolites, by-products of microbial fermentation, chitosan, oligosaccharides, and silicon-based compounds, which may contribute to improved nutrient uptake, stress resistance, and cellular structural integrity under specific conditions [17,24,28].

Advances in biological processing and molecular characterization have further accelerated biostimulant innovation. Bioactive peptides associated with both nutrient assimilation and antioxidant responses have been produced by enzymatic hydrolysis, and auxin-like substances have been identified through functional fractionation of humic substances, which are linked to root growth and nutrient mobilization [47–49]. These developments reflect a clear trend toward more targeted, crop-specific, and scientifically optimized biostimulant formulations (Fig. 2).

### 3.4. Multi-Component and Consortia Formulations

Recent research has focused on multi-component formulations that combine microbial and plant-derived stimulants to achieve synergistic

outcomes. Such combinations have shown potential to concurrently improve root development, nutrient acquisition, and abiotic stress tolerance through coordinated regulation of metabolic and transport pathways [21].

Studies in MAPs indicate that different classes of biostimulants, including AMF, PGPR, seaweed extracts, humic substances, and protein hydrolysates, can improve biomass accumulation, essential oil production, nutrient acquisition, stress tolerance, and phytochemical quality [25,27–29,31,32,38]. Combining different biostimulant classes may provide complementary effects. However, the magnitude and consistency of these interactions depend on the crop, formulation, dose, application method, and environmental conditions [28,31,32,38].

Despite these advances, their field performance remains influenced by formulation stability, compatibility among components, crop specificity, and environmental variability. Future research should therefore focus on optimizing formulation design, validating efficacy across diverse agroecological conditions, and establishing standardized evaluation protocols to facilitate commercial adoption [29,32].

### 3.5. Precision Delivery and Digital Integration Technologies

Biostimulant applications are increasingly being integrated with digital agriculture and precision-delivery technologies to improve application efficiency and resource management. Remote-sensing tools, including

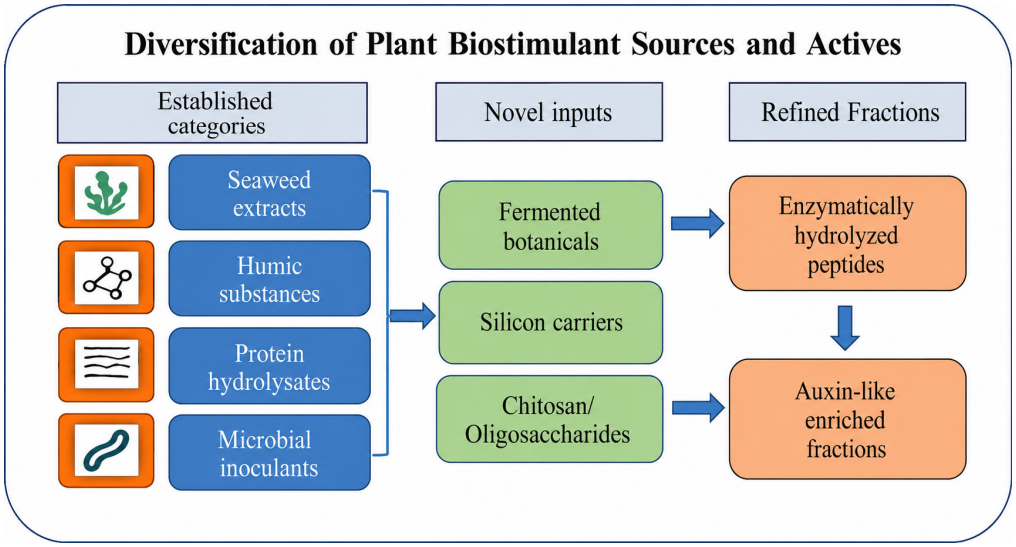


**Figure 2.** Established biostimulant categories, including seaweed extracts, humic substances, protein hydrolysates, and microbial inoculants, have expanded into novel inputs such as fermented botanicals, silicon carriers, and chitosan oligosaccharides. These materials can be further refined into bioactive fractions, including enzymatically hydrolyzed peptides and auxin-like compounds, to enhance crop performance and stress resilience.

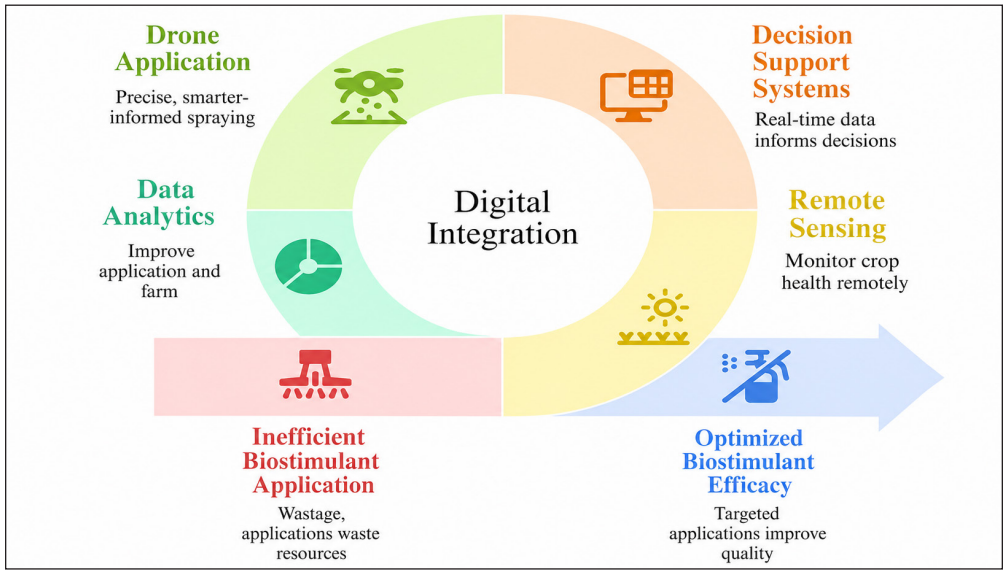


**Figure 3**. The integration of digital agriculture tools, including drone application, remote sensing, data analytics, and DSSs, to enable precision biostimulant application. Real-time monitoring and site-specific decision-making improve application accuracy, optimize resource use, reduce input losses, and enhance crop productivity, stress resilience, and the sustainability of MAPs cultivation.

multispectral and thermal imaging linked with DSSs, may support real-time crop monitoring and optimized application strategies under stress conditions such as drought and heat [50].

In MAPs, application timing is particularly important because secondary metabolite accumulation is highly dependent on developmental stage and environmental conditions. Sensor-guided and site-specific application approaches can improve the precision and efficiency of input delivery, potentially reducing input losses. UAV- and drone-based spraying systems represent an emerging precision-agriculture technology for targeted crop-input application; however, their specific use for biostimulant delivery in MAP production remains insufficiently validated and requires further field-scale evaluation [51]. In addition, machine learning and DSS platforms may assist in refining biostimulant management strategies using environmental and crop-performance data [50,51].

Overall, digital monitoring and precision-delivery technologies show potential to improve the consistency and efficiency of biostimulant application in high-value MAP production systems (Fig. 3).

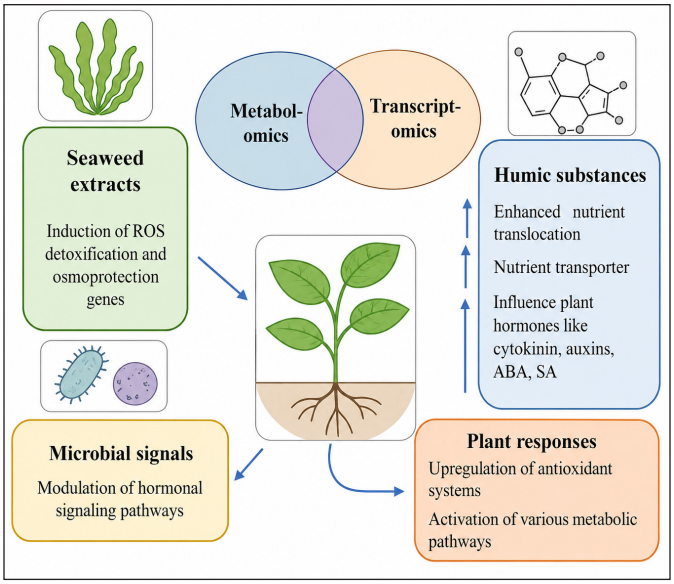


**Figure 4.** Integrated omics analyses reveal that PBs regulate gene expression and metabolic pathways involved in hormone signaling, nutrient transport, antioxidant defense, ROS homeostasis, osmoprotection, and stress adaptation, thereby enhancing plant growth, resilience, and productivity.

### 3.6. Mechanistic Resolution via "Omics"

Omics technologies, particularly transcriptomics and metabolomics, have improved understanding of the molecular mechanisms underlying biostimulant activity. These approaches reveal substantial variation in gene expression and metabolic pathways in response to different biostimulant stimuli, with implications for stress adaptation, nutrient uptake, and cellular homeostasis [33,34].

Transcriptomic and gene-expression studies in MAPs have shown that biostimulant treatments can modulate antioxidant enzymes, stress-responsive transcription factors, and genes involved in secondary-metabolite biosynthesis [52,53]. Biostimulants have also been shown to modulate hormonal signaling networks governing growth and stress responses [26].

Omics-based approaches offer valuable insight into PB mechanisms and formulation strategies, but there remains a challenge to bring discovery to commercially viable and field-appropriate products (Fig. 4).

### 3.7. Climate Resilience Focus

Biostimulants have gained potential in addressing environmental stresses such as drought, salinity, and heat in plants. It has been established that, under certain conditions, microbial biostimulants can lead to improved water use efficiency, ionic balance, and stress tolerance [25,54,55]. Their field performance, however, has been variable, attributable to the influence of the environment, interactions between soil microbes, and concerns about biosafety in large-scale microbial applications. Likewise, the use of biostimulants has been

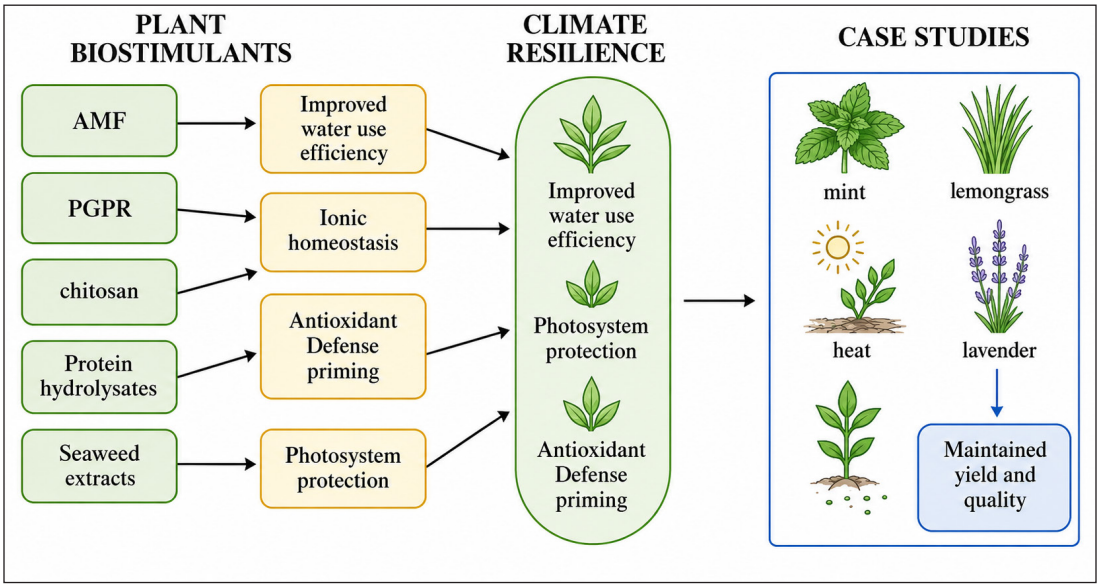


**Figure 5**. PBs, including AMF, PGPR, chitosan, protein hydrolysates, and seaweed extracts, improve key physiological processes associated with water-use efficiency, ionic homeostasis, antioxidant defense, and photosystem protection. These responses enhance tolerance to drought, salinity, and heat stress, thereby sustaining yield and quality in medicinal and aromatic crops.

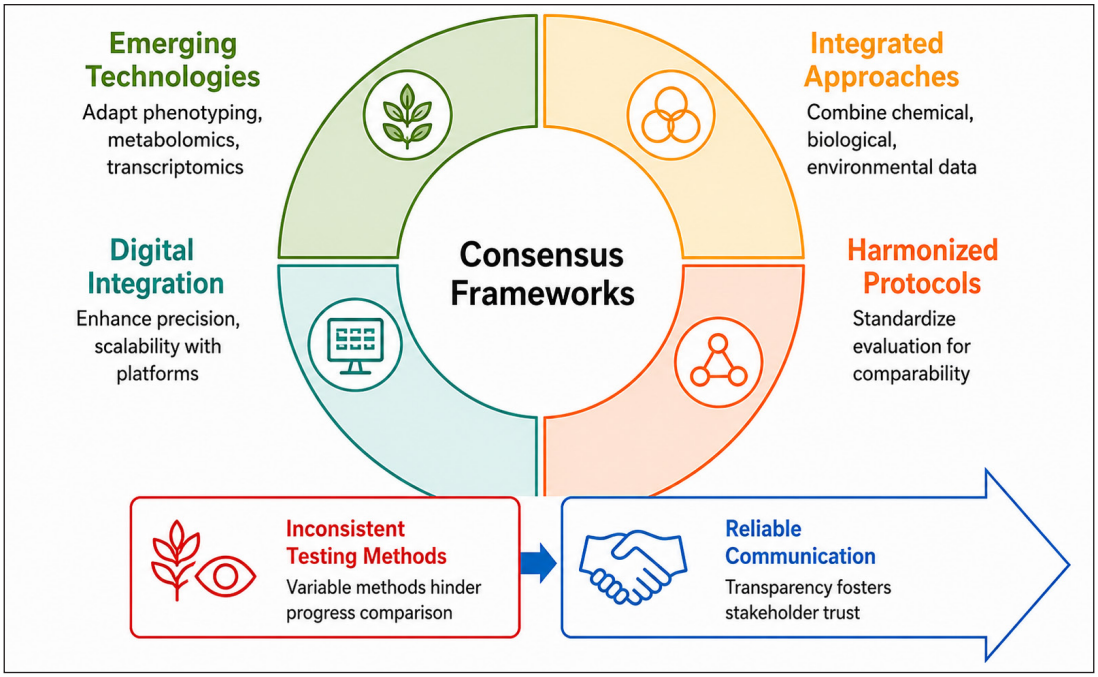


**Figure 6.** Emerging technologies, integrated analytical approaches, harmonized testing protocols, and digital platforms support the development of consensus frameworks that improve scientific validation, product comparability, regulatory compliance, and the commercial adoption of PBs.

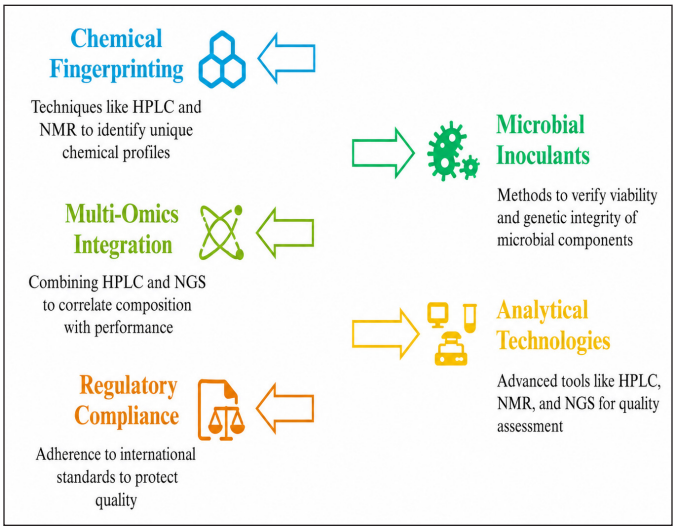


**Figure 7**. Integrated analytical tools, including chemical fingerprinting, molecular characterization, and multi-omics technologies, support product authentication, quality assurance, standardization, and regulatory compliance while ensuring the consistency and reliability of commercial biostimulant formulations.

reported as a mechanism for maintaining the oxidative stability and photosensitivity of plants under abiotic stress conditions [19,56,57].

They can regulate hormone signaling, ion transport, and secondary metabolic pathways under stress conditions. Transcriptomic data specific to MAPs remain limited, though early findings suggest potential regulation of terpenoid and phenolic biosynthetic routes linked to stress adaptation.

Several MAP studies have examined the maintenance of essential oil content in mint under drought stress, the reduced salinity effects on lavender, and increased yield and withanolide accumulation in ashwagandha under stress conditions [58–62]. Most evidence to date, however, comes from greenhouse systems or short-term tests, and long-term field testing in MAP remains limited (Fig. 5).

### 3.8. Regulation, Standardization, and Testing Challenges

The PB field has made considerable strides in regulatory advancement over the past few years. In 2019, the EU Fertilising Products Regulation (EU 2019/1009) introduced a harmonized approach to claims concerning nutrient-use efficiency and abiotic stress tolerance for the safety, labelling and scientific evidence required to justify these claims [23,63,64]. Other regulations are also being introduced in Canada, Brazil, and other parts of Asia, leading to enhanced transparency and product standardization [65,66].

There are steps forward, but efficacy assessment is going on a limited scale all over the world. Comparisons between various studies can be complicated by some crop models, by differing sets of environmental parameters, by differing experimental designs, and by differing testing methods, while large-scale validation may be problematic [19,20,67]. Furthermore, with such complexity, a detailed chemical, biological, and mechanistic characterization of PBs to elucidate their bioactive agents and microbial consortia is required [20,68]. More advanced techniques such as metabolomics, transcriptomics, high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), liquid chromatography-mass spectrometry (LC-MS), and next-generation sequencing (NGS) are being used to improve product characterization, quality control, and reproducibility more and more [50,68,69]. However, the specific guidelines and procedures for testing biostimulants vary widely around the world, which makes the broad commercialization and scientific evaluation of PBs more complex (Fig. 6).

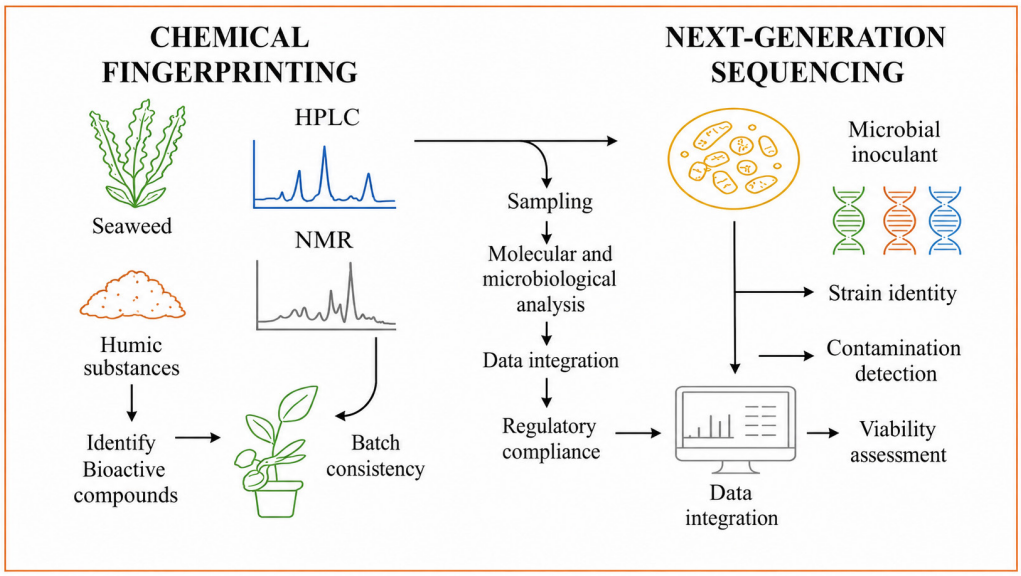


**Figure 8.** Using integrated analytical and molecular methods to characterize and assess the quality of PBs. An extensive flow chart for the determination of the quality of PBs by combining chemical, molecular, and microbiological analyses. The analysis of the sources of biostimulants, such as extracts of seaweeds and humic substances, for the presence of bioactive compounds is carried out by the methods of chemical fingerprinting, including HPLC and NMR, to ensure batch consistency. At the same time, microbial inoculants can be identified, viability verified, and screened for microbial contamination by using NGS and microbiological analysis. Analytical and molecular data enable regulatory compliance, product standardization and quality assurance, and improve the affected products' reliability, efficacy, and commercial value for PB products.

### 3.9. Quality Control and Authentication

There is also a concern over mislabeling, batch variation, and product adulteration, which necessitates quality control and authentication to assure the safety, uniformity, and reliability of PBs. Advanced analytical techniques are crucial for the accurate characterization and regulatory compliance of such complex natural-origin raw materials as humic substances, seaweed extracts, and microbial compositions (Fig. 7).

Chemical composition and formulation characteristics of PBs can be evaluated using chromatographic and spectroscopic techniques, including HPLC, GC-MS, LC-MS, and NMR, to support product characterization and quality control [70–72]. NMR-based methods facilitate chemical profiling and quality assessment of complex botanical products, while NMR- and LC-MS-based metabolomic approaches can provide detailed information on the chemical and metabolic profiles of biostimulant formulations [19,71]. Microbial identity and genomic characteristics can be investigated using NGS approaches. However, conventional NGS detects microbial genetic material and cannot by itself distinguish viable from non-viable microorganisms; therefore, NGS should be considered a tool for microbial identification and genomic characterization rather than a direct method for determining microbial viability [73] (Fig. 8).

The physicochemical, molecular, and microbiological analysis integration helped in the authentication of products, batch consistency, and increased scientific transparency in the field of biostimulants [70,72]. New methods for quality control, however, have not yet gained substantial acceptance because of the absence of globally agreed-upon standards and validation procedures.

In conclusion, the analytical techniques, HPLC, NMR, GC-MS, LC-MS, and NGS, address most of the significant concerns in the authentication and quality of biostimulants. They reduce the risk of fraud, reduce the variability of batches, and enhance stakeholder confidence. Continuous improvement and harmonization of practices is an important element that would establish high global quality standards in the expanding biostimulant sector.

### 3.10. Market Growth and Economics

There has been a growing demand for sustainable agricultural inputs, including PBs, which could enhance crop productivity, quality, and stress tolerance, contributing to the rapid growth of the PB market worldwide [16,74]. The global biostimulants market is projected to reach USD 8.77 billion by 2031, growing at a compound annual growth rate (CAGR) of 12.0% during 2026–2031. In India, the biostimulants market is projected to reach USD 1.136 billion by 2032, with a CAGR of 15.64% during 2025–2032 [75,76].

In MAPs, PB application has been associated with improvements in essential oil content, phytochemical quality, and crop value under certain production conditions [77,78]. Economic benefits may occur under specific production conditions, but remain dependent on crop, formulation, application strategy, and input costs [10,79,80]. However, economic results are uncertain and vary according to crop type, environmental conditions, product formulation, and/or management practices. However, additional long-term economic evaluations and region-specific validity tests are required to enable broader commercialization [81].

### 3.11. Field-Level Adoption and Commercial Challenges

Although extensive experimental evidence shows promise, the high market share adoption of PBs in MAP production is still limited by a number of practical issues. The variability of the environment and diversity in soil, genotype, formulation stability, and application methods cause a very uneven response in the field [16,17,20,82]. Moreover, the price of some commercial products is very high,

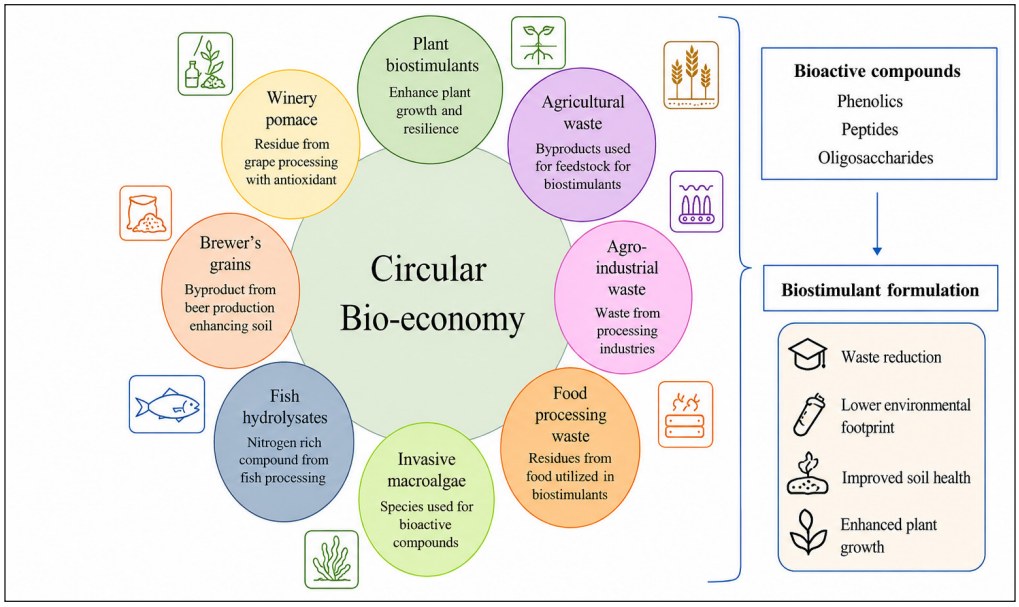


**Figure 9.** Waste-derived materials for sustainable biostimulant formulation within a circular bioeconomy framework. The figure illustrates how residues from agriculture, agro-industry, food processing, wineries, breweries, fish processing, and invasive macroalgae can be valorized as renewable feedstocks for PB production. These waste streams contain bioactive compounds, including phenolics, peptides, and oligosaccharides, which can be recovered and incorporated into biostimulant formulations. By transforming biological residues into value-added agricultural inputs, circular bioeconomy approaches reduce waste generation, lower environmental impacts, improve resource-use efficiency, and contribute to enhanced soil health, plant growth, and agricultural sustainability.

insufficient awareness among farmers, and a lack of adequate recommendations for the various sites and production conditions are also limiting the wider use, especially in smallholder farming. Regulatory inconsistencies, lack of harmonized efficacy protocols, and variability in product quality further complicate commercialization and market confidence [19,66,72,83,84]. Therefore, greater emphasis on long-term field validation, economic assessment, formulation standardization, and farmer-oriented extension programs will be essential for the reliable integration of biostimulants into sustainable MAP production systems.

### 3.12. Circular Bioeconomy Inputs

The incorporation of PBs into circular bioeconomy systems can enhance resource efficiency and agricultural sustainability. In particular, agricultural and agro-industrial wastes and by-products can be valorized as feedstocks for the production of biostimulants, thereby converting low-value waste streams into useful agricultural inputs, reducing waste generation and potentially lowering the environmental footprint associated with conventional crop inputs. Such approaches can contribute to nutrient recycling, resource recovery and sustainable intensification of agricultural production [85].

Biostimulants derived from circular bioeconomy resources have the potential to reduce environmental impacts by valorizing agricultural wastes and improving resource-use efficiency. Life-cycle assessments indicate that the environmental footprint of biostimulant production depends on production processes, energy inputs, packaging, and allocation assumptions, highlighting opportunities to reduce impacts through process optimization [86,87]. Agricultural biotechnology combined with the principles of the circular economy contributes to closed-loop systems that enhance crop performance with minimal ecological effects (Fig. 9).

### 3.13. Critical Perspectives and Limitations of Biostimulants

Although the scientific and commercial interest in PBs has been growing, their effectiveness is very crop- and formulation-dependent as well as dependent on environmental conditions [88–90]. However, several studies have reported inconsistent, limited, or insignificant responses under field conditions, with concerns that the formulations might be unstable and that there was variation in active components and lack of reproducibility among various experimental systems [91–96]. In some cases, biostimulant applications may produce limited or inconsistent effects compared with conventional management, particularly when formulation, application rate, timing, or application method is not appropriately optimized. Such variability can result in neutral or, under certain conditions, adverse plant responses, highlighting the need for crop-specific and environment-specific optimization and field validation [93].

Biological interactions between plants, microorganisms, soil properties, environmental factors, and site characteristics add to the environmental variability of PB performance. Lack of scientific understanding, limited independent validation studies, and lack of harmonized testing protocols also still limit wider scientific trust and commercial standardization. While recent progress in molecular and omics-based research has led to a better understanding of mechanisms, there is still a need for increased focus on long-term field testing at multiple locations to validate their efficacy with sufficient consistency and sustainability to support their use in MAP production systems.

## 4. FUNCTIONAL PROSPECTIVE OF BIOSTIMULANTS ON MEDICINAL AND AROMATIC CROPS

The PBs are substances and microorganisms that can regulate the physiological and biochemical processes in MAPs and thus enhance their growth, nutrient-use efficiency, stress tolerance, and production

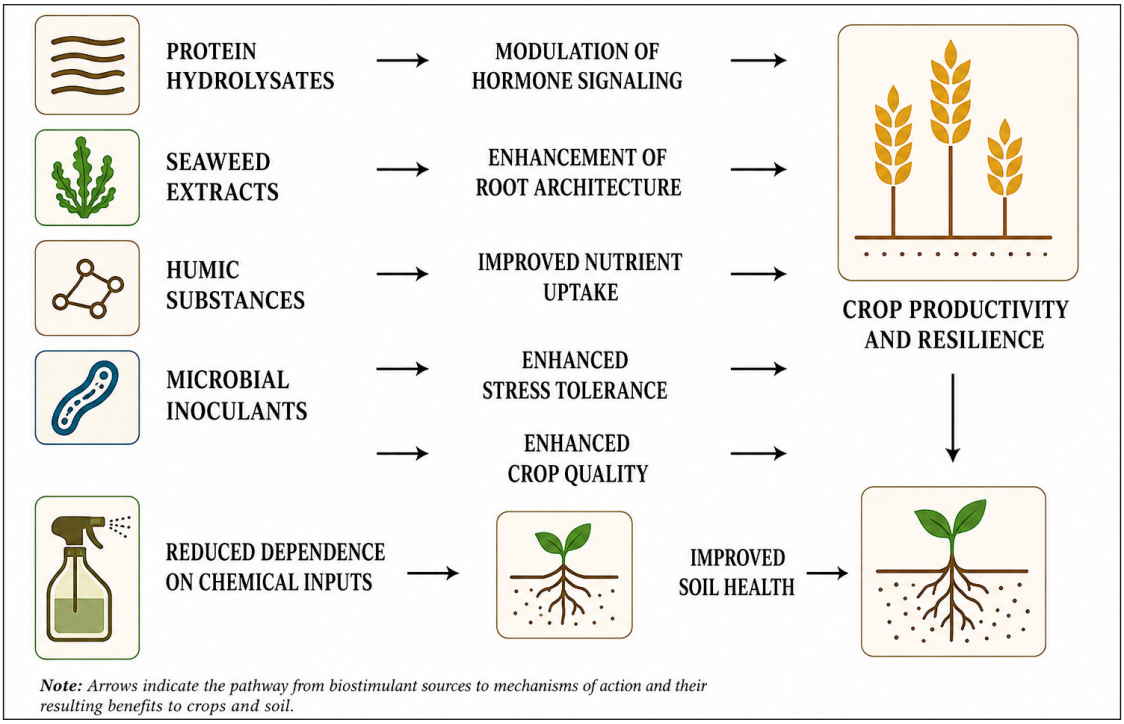


**Figure 10.** Increase in crop productivity, stress tolerance, and soil quality through biostimulants. The figure suggests the main mechanisms by which various types of PBs can enhance sustainable crop production. Protein hydrolysates interact with hormone signaling pathways, seaweed extracts stimulate root development, humic substances increase plant nutrient uptake and utilization, and microbial inoculants help plants resist stress and produce good quality crops. These combined physiological and biochemical mechanisms enhance the production, abiotic stress tolerance, and resource-use efficiency of plants. Additionally, lowering reliance on chemical inputs promotes good soil health, ensuring longer-term agricultural sustainability and ecosystem health.

of phytochemicals [9,19,21]. Their documented benefits, which span root development, nutrient-use efficiency, stress tolerance, and secondary metabolite accumulation, have been reviewed in detail in Sections 3.1 to 3.3 [16,30,48,49].

In MAP production systems, PBs can play a role in decreasing reliance on synthetic inputs increase crop productivity and resilience [16,20]. Their effectiveness, however, remains highly dependent on crop species, environmental conditions, and formulation characteristics. Overall, PBs represent a promising approach for sustainable MAP cultivation, although further field validation and standardization are still required [97] (Fig. 10).

### 4.1. Uses of Biostimulants in Medicinal and Aromatic Crops

PBs are also emerging in MAP farming systems due to their potential to modulate resilience, productivity, and phytochemical profile through integrated plant-soil-microbe interaction responses, their effectiveness remains context-dependent and variable across conditions [98]. On the one hand, they can control the synthesis of secondary metabolites, enhance nutrient-use efficiency, and enhance plant–microbe interaction to ensure sustainable MAP generation [99].

Biostimulants can support plant adaptation to abiotic stresses including salinity, drought, and temperature extremes by activating antioxidant defense mechanisms and maintaining osmotic balance, thereby stabilizing yield and phytochemical production [26]. Nevertheless, PB responses in MAPs remain species-specific and highly dependent on environmental and management conditions (Table 1).

#### *4.1.1. Influence on agronomic and physiological traits of crops*

PBs may improve agronomic and physiological traits in MAPs by influencing plant growth, root development, and resource-use efficiency [21]. Several studies have reported increases in plant height, biomass accumulation, leaf development, and photosynthetic activity following PB application under specific conditions [16] (Fig. 11).

The potential of PBs to mitigate abiotic stresses, including drought, salinity, and high temperature in MAPs, is an area of increasing research attention [21, 26]. Their effects are associated with regulation of antioxidant activity, osmotic balance, ion homeostasis, and stress-related metabolic processes under specific conditions.

PBs show potential to support sustainable intensification of MAP production systems; however, their effectiveness remains dependent on crop species, environmental conditions, and formulation characteristics.

#### *4.1.2. Improving nutrient use efficiency*

Efficient nutrient management is essential for maintaining biomass production and secondary metabolite accumulation in MAPs [7, 21]. Depending on the species and the conditions, PBs can be beneficial to increase nutrient use efficiency and therefore help sustainable nutrient management by increasing nutrient uptake, rhizosphere effects, and root activities [16, 20, 21, 80].

The potential of PBs for nutrient-use efficiency and crop quality in MAP systems exists, but their effectiveness is greatly influenced by soil characteristics, microbial dynamics, environmental conditions, and formulation-specific characteristics.

**Table 1.** Trials conducted on different crops using different biostimulants and their impact on crops.

| S. no. | Biostimulant used | Crop species | Major effects | References |
|---|---|---|---|---|
| 1. | Weed leaf extract | *W. somnifera* | Increased root biomass, withanolide content, and yield | [100] |
| 2. | Plant-derived protein hydrolysates | *O. basilicum* cultivars | Increased fresh yield, leaf area, and net $CO_2$ assimilation under the tested hydroponic conditions | [101] |
| 3. | Humic acid | *Origanum vulgare* | Improved biomass, essential oil content, and antimicrobial activity | [30] |
| 4. | Legume-based protein hydrolysates | *Cannabis sativa* | Enhanced photosynthesis, seed yield, and salinity tolerance | [102] |
| 5. | *Malva parviflora* extract + humic acid | *Lavandula latifolia* | Improved growth, yield, and essential oil composition | [103] |
| 6. | Seaweed extract foliar spray | *Hyssopus officinalis* | Increased biomass and essential oil yield | [104] |
| 7. | *Moringa oleifera*, *Aloe vera*, and *Spirulina platensis* extracts | *Lavandula* spp. | Enhanced phenolic compounds and oil quality | [105] |
| 8. | Algae and yeast extracts | *Rosmarinus officinalis* | Improved growth, yield, and essential oil composition | [40] |
| 9. | Moringa leaf extract | *Nigella sativa* | Increased plant growth, oil content, and yield quality | [106] |
| 10. | Moringa leaf extract | Sweet basil (*O. basilicum*) | Mitigated salinity stress and improved biochemical responses | [107] |
| 11. | Seaweed extract | *Pelargonium graveolens* | Enhanced growth, herbage yield, and oil quality | [108] |
| 12. | *Solieria chordalis* seaweed extract | *Pogostemon cablin* | Increased biomass, oil yield, and oil quality | [78] |
| 13. | Tulsi extract | *Nicotiana tabacum* | Improved in vitro regeneration and embryogenesis | [109] |
| 14. | Seaweed liquid extract | *Cymbopogon citratus* | Increased herb yield, oil yield, and nutrient efficiency | [110] |
| 15. | *Kappaphycus alvarezii* extract | *Pelargonium graveolens* | Enhanced growth, herbage yield, and oil composition | [111] |
| 16. | Moringa leaf extract | *Pelargonium graveolens* | Increased biomass, phenolics, antioxidants, and oil yield | [112] |
| 17. | Microbial consortium | *Withania somnifera* | Organic nutrient management involving manures and microbial consortium | [113] |
| 18. | Microbial consortium | *Andrographis paniculata* | Organic nutrient management involving manures, microbial consortium, and biodynamic preparation | [114] |
| 19. | Protein hydrolysates and tropical plant extracts | Perennial wall rocket (*Diplotaxis tenuifolia*) | Improved yield, biomass, and nutritional quality | [115] |

The table presents a representative selection of primary experimental studies rather than the complete body of literature considered in the review. Studies were selected based on their direct relevance to MAPs, clearly defined biostimulant treatments, availability of experimental data, and reporting of measurable agronomic, physiological, biochemical, yield, or phytochemical outcomes. The selected studies were also intended to represent major biostimulant classes, MAP species, application approaches, and response categories discussed in the review.

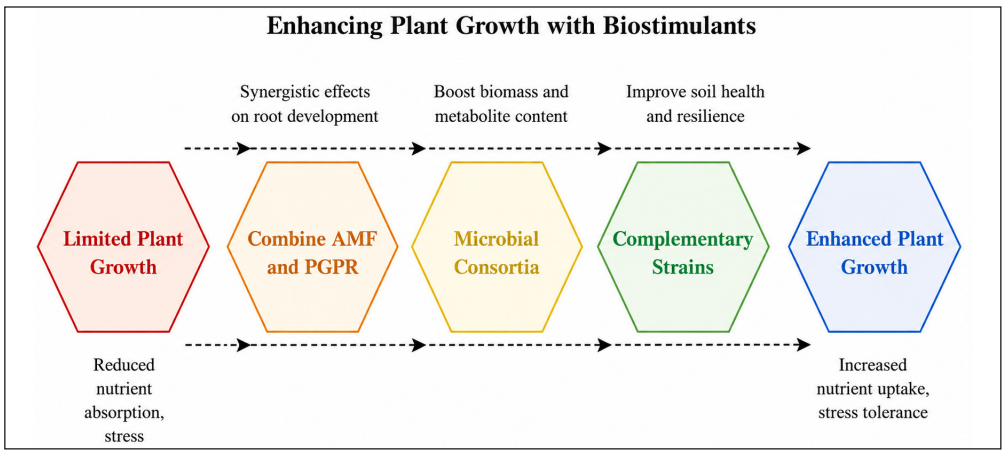


**Figure 11.** Synergistic role of AMF, PGPR, and microbial consortia in enhancing plant growth and stress tolerance. The figure illustrates how the combined application of AMF, PGPR, and diverse microbial consortia can enhance plant performance through complementary and synergistic mechanisms. These beneficial microorganisms improve root development, nutrient acquisition, and microbial interactions within the rhizosphere, leading to increased biomass accumulation and enhanced metabolite production. Their collective action also strengthens soil health, promotes stress resilience, and improves nutrient-use efficiency, ultimately resulting in enhanced plant growth and greater tolerance to biotic and abiotic stresses.

### *4.1.3. Enhancing produce quality*

For MAPs, quality is a crucial determinant of their medicinal and commercial value. Important quality attributes include essential-oil content and composition, phytochemical profiles, fragrance characteristics, and antioxidant activity, which can vary according to plant species, genotype, cultivation conditions, harvest stage, and post-harvest handling [116, 117]. PBs are linked to better quality of phytochemicals and increased production of secondary metabolites under certain conditions, but there are also cases in which several crop species exhibit different reactions to stimulation [53].

Phytochemical responses are, however, highly crop-specific and can depend on environmental conditions and formulation characteristics. Moreover, the presence of contaminants, including heavy metals, emphasizes the need for rigorous quality-assurance and traceability protocols for biostimulant products to ensure their safety, consistency, and reliability in the market [118]. Overall, PBs show considerable promise for enhancing phytochemical quality and secondary metabolite production in MAPs. However, additional optimization and field testing for each crop is still required.

#### *4.1.4. Effect on soil microbiota*

Biostimulants can also contribute to the health and long-term sustainability of MAP production systems following their initial effects on plant physiology [30]. Certain biostimulants, particularly those containing beneficial microorganisms or organic biostimulant components, can influence the soil microbial community and rhizosphere processes, supporting microbial activity, nutrient cycling, organic matter transformation, and soil biological resilience [10, 18].

### 4.2. Variability and Context-Dependent Outcomes

More recently, the PBs are of growing interest, yet their efficacy is less consistent, and results are not always repeatable in various production systems. There have been reports of plants with little or no modification to their growth, biomass, yield, or phytochemical production under ideal plant growth conditions, which may have high levels of phytochemical production from the start [10, 17, 19, 20].

Under field conditions, the variability of PB responses can be even greater and can arise from soil heterogeneity and climatic and genetic differences of the crop and associated microbial communities [16, 18]. Moreover, chemical composition, physical stability of the formulation, dosage, and timing of application may significantly affect treatment results [9, 19, 71]. Sometimes the application rates are far above or far below the recommended levels, or the formulation is not appropriate for a given crop or stage of growth, leading to insignificant or even adverse physiological response [19–21].

PBs can be regarded as context-specific interventions to be optimized for each crop and thoroughly proven across multiple environments under field conditions before generic recommendations are made.

## 5. CONCLUSION

Over the past decade, PBs have demonstrated considerable promise as tools for the sustainable cultivation of MAPs. The available data suggest that PBs such as microbial inoculants, seaweed extracts, humic substances, protein hydrolysates, and chitosan-based products can improve plant growth rates, nutrient-use efficiency, stress resistance, soil biological activities, and production of secondary metabolites. In MAP systems, these effects can contribute to enhanced crop productivity and phytochemical quality. There is, however, a strong crop-specific response for PB formulations, as well as variability with respect to environmental conditions, dosage, and how the formulations are applied in the field, and there are also some reports of inconsistent field performance.

Although the scientific and commercial interest in PBs has grown, certain obstacles remain to their widespread use in MAP production. Batch-to-batch variation in raw materials, formulation characteristics, or the environment can often lead to failures in efficacy during field use. Furthermore, short-term and place-based testing limits the ability to test the performance of PB in various agro-climatic regions. Regulatory inconsistencies, non-standardized testing procedures, and insufficient economic evaluation further constrain commercialization and farmer adoption.

Further studies should be extended in the field with long-term validation, formulation standardization, and incorporation of omics data in an agronomic application package. There should also be more focus on dose optimization, economic viability, regulatory harmonization, and management approaches that are farmer-friendly, especially in smallholder systems. Ultimately, interdisciplinary and evidence-based research, spanning agronomy, plant physiology, molecular biology, and regulatory science, will be essential for realizing the reliable and scalable integration of PBs into MAP cultivation systems.

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## 7. AUTHOR CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agree to be accountable for all aspects of the work. All the authors are eligible to be authors as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

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## 9. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

## 10. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

## 11. DATA AVAILABILITY

All the data are available with the authors and shall be provided upon request.

## 12. PUBLISHER'S NOTE

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## 13. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors prepared the schematic illustrations and graphical representations in this manuscript using BioRender and Canva AI. AI assistance was limited to visual elements, including figure layout, arrangement of graphical components, and refinement of illustrations for clarity and presentation. The scientific concepts, figure content, interpretation, and final selection of visual elements were determined and verified by the authors. AI tools were not used to generate or interpret scientific data, results, or conclusions. The authors reviewed and approved all figures and take full responsibility for their accuracy, originality, and scientific integrity.

## REFERENCES


1. Türkekul B, Yildiz O. Medicinal and aromatic plants production, marketing and foreign trade. In: MEDICINAL AND AROMATIC PLANTS: economics Production Agricultural Ultilization and Other Aspects. İKSAD Publishing House; 2021. p. 3–44; Available from: https://www.researchgate.net/publication/357434305_Medicinal_and_Aromatic_Plants_Production_Marketing_and_Foreign_Trade
2. Shukla S, Patra D, Sinha A, Saha R, Tripathi Y, Borah NK, *et al.* Medicinal and aromatic plant cultivation, improvement and conservation for sustainable development. In: Industrial crops improvement: biotechnological approaches for sustainable agricultural development. Cham, Switzerland: Springer Nature Switzerland; 2025. 183–204 pp; doi: https://doi.org/10.1007/978-3-031-75937-6_11
3. Balkrishna A, Srivastava D, Sharma N, Parveen R, Kukreti A, Arya V. Global Trends in the Integration of Traditional and Modern Medicine: challenges and Opportunities. Future Integr Med 2025;4(4):217–32; doi: https://doi.org/10.14218/FIM.2025.00040
4. Zamani S, Fathi M, Ebadi MT, Máthé A. Global trade of medicinal and aromatic plants. A review. J Agriculture Food Res 2025;21:101910; doi: https://doi.org/10.1016/j.jafr.2025.101910
5. Chowti PS, Rudrapur S, Naik BK. Production scenario of medicinal and aromatic crops in India. J Pharmacogn Phytochem 2018;7(3S):274–7.
6. NITI Aayog. Strategic roadmap for making Ayurveda global [Internet]. New Delhi: NITI Aayog, Government of India; 2026 [cited 2026 Aug 30]. Available from: https://www.niti.gov.in/sites/default/files/2026-07/Strategic-Roadmap-for-Globalization-of-Ayurveda.pdf
7. Mahato D, Mahto H, Kumari S. Medicinal and aromatic plant cultivation and sustainable development. In: Industrial Crops Improvement: biotechnological Approaches for Sustainable Agricultural Development 2025 pp. 135-153. Springer Nature Switzerland; 2025. 135–53 pp; doi: https://doi.org/10.1007/978-3-031-75937-6_8
8. Sun Y, Alseekh S, Fernie AR. Plant secondary metabolic responses to global climate change: a meta-analysis in medicinal and aromatic plants. Global Change Biol 2023;29(2):477–504; doi: https://doi.org/10.1111/gcb.16484
9. Du Jardin P. Plant biostimulants: definition, concept, main categories and regulation. Scientia Horticulturae 2015;196:3–14; doi: https://doi.org/10.1016/j.scienta.2015.09.021
10. Rouphael Y, Colla G. Editorial: Biostimulants in agriculture. Front Plant Sci 2020;11:40; doi: https://doi.org/10.3389/fpls.2020.00040
11. Shahrajabian MH, Sun W. Sustainable approaches to boost yield and chemical constituents of aromatic and medicinal plants by application of biostimulants. Recent Adv Food Nutr & Agriculture 2022;13(2):72–92; doi: https://doi.org/10.2174/2772574X13666221004151822
12. Ismail MA, Ahmad M, Abdelrahman T, Marwa A, Sally A, Ali M. Amino acids and polyamines in foliar spraying in enhancing medicinal plant resilience to abiotic stress–A systematic review. J Angiotherapy 2024;8(11):1–5; doi: https://doi.org/10.25163/angiotherapy.81110082
13. Ruzzi M, Colla G, Rouphael Y. Biostimulants in agriculture II: towards a sustainable future. Front Plant Sci 2024;15:1427283; doi: https://doi.org/10.3389/fpls.2024.1427283
14. Landeta C, Marchant F. Biostimulants: Emerging trend and opportunities. Biostimulants: Exploring sources and applications. 2022:263–90; doi: https://doi.org/10.1007/978-981-16-7080-0_11
15. Mishra H. Nanobiostimulants and precision agriculture: a data-driven approach to farming and market dynamics. In: Nanobiostimulants: emerging strategies for agricultural sustainability 2024 Nov 12. Springer Nature Switzerland; 2024. 365–98 pp; doi: https://doi.org/10.1007/978-3-031-68138-7_16
16. Calvo P, Nelson L, Kloepper JW. Agricultural uses of plant biostimulants. Plant Soil 2014;383(1):3–41; doi: https://doi.org/10.1007/s11104-014-2131-8
17. Bulgari R, Cocetta G, Trivellini A, Vernieri P, Ferrante A. Biostimulants and crop responses: a review. Biol Agriculture & Horticulture 2015;31(1):1–7; doi: https://doi.org/10.1080/01448765.2014.964649
18. Backer R, Rokem JS, Ilangumaran G, Lamont J, Praslickova D, Ricci E, *et al.* Plant growth-promoting rhizobacteria: context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. Front Plant Sci 2018;9:1473; doi: https://doi.org/10.3389/fpls.2018.01473
19. Yakhin OI, Lubyanov AA, Yakhin IA, Brown PH. Biostimulants in plant science: a global perspective. Front Plant Sci 2017;7:2049; doi: https://doi.org/10.3389/fpls.2016.02049
20. Colla G, Hoagland L, Ruzzi M, Cardarelli M, Bonini P, Canaguier R, *et al.* Biostimulant action of protein hydrolysates: unraveling their effects on plant physiology and microbiome. Front Plant Sci 2017;8:2202; doi: https://doi.org/10.3389/fpls.2017.02202
21. Rouphael Y, Colla G. Synergistic biostimulatory action: designing the next generation of plant biostimulants for sustainable agriculture. Front Plant Sci 2018;9:1655; doi: https://doi.org/10.3389/fpls.2018.01655
22. Huygens D, Saveyn H, Tonini D, Eder P, Delgado SL. Technical proposals for selected new fertilising materials under the Fertilising Products Regulation (Regulation (EU) 2019/1009), EUR 29841 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-09888-1, JRC117856; doi: https://doi.org/10.2760/186684
23. Barros-Rodríguez A, Rangseekaew P, Lasudee K, Pathom-Aree W, Manzanera M. Regulatory risks associated with bacteria as biostimulants and biofertilizers in the frame of the European Regulation (EU) 2019/1009. Sci Total Environ 2020;740:140239; doi: https://doi.org/10.1016/j.scitotenv.2020.140239
24. Folina A, Kakabouki I, Baginetas K, Bilalis D. Integration of bioresources for sustainable development in organic farming: a comprehensive review. Resources 2025;14(7):102; doi: https://doi.org/10.3390/resources14070102
25. Israel A, Langrand J, Fontaine J, Lounès-hadj Sahraoui A. Significance of arbuscular mycorrhizal fungi in mitigating abiotic environmental stress in medicinal and aromatic plants: a review. Foods 2022;11(17):2591; doi: https://doi.org/10.3390/foods11172591
26. Hasanuzzaman M, Parvin K, Bardhan K, Nahar K, Anee TI, Masud AAC, *et al.* Biostimulants for the regulation of reactive oxygen species metabolism in plants under abiotic stress. Cells 2021;10(10):2537; doi: https://doi.org/10.3390/cells10102537
27. Elumalai S, Alagarswamy S, Janaki P, Kuppusamy S, Geethanjali S, Parasuraman B. Exploring seaweed potential to enhance abiotic stress tolerance of crops. Russian J Plant Physiol 2025;72(3):86; doi: https://doi.org/10.1134/S1021443725600370
28. Rathor P, Gorim LY, Thilakarathna MS. Plant physiological and molecular responses triggered by humic based biostimulants-a way forward to sustainable agriculture. Plant Soil 2023;492(1):31–60; doi: https://doi.org/10.1007/s11104-023-06156-7
29. Nardi S, Schiavon M, Francioso O. Chemical structure and biological activity of humic substances define their role as plant growth promoters. Molecules 2021;26(8):2256; doi: https://doi.org/10.3390/molecules26082256
30. Aytaç Z, Gülbandılar A, Kürkçüoğlu M. Humic acid improves plant yield, antimicrobial activity and essential oil composition of Oregano (Origanum vulgare L. subsp. hirtum (Link.) Ietswaart). Agronomy 2022;12(9):2086; doi: https://doi.org/10.3390/agronomy12092086
31. Sun W, Shahrajabian MH, Kuang Y, Wang N. Amino acids biostimulants and protein hydrolysates in agricultural sciences. Plants 2024;13(2):210; doi: https://doi.org/10.3390/plants13020210
32. Weisany W, Khosropour E, Alavian A. Application of microbial consortia and biofertilizer to improve the quality and yield of essential oils in aromatic plants. In: Plant Essential Oils: from Traditional to Modern-day Application 2023 Dec 10. Singapore: Springer Nature Singapore; 2023. 205–23 pp; doi: https://doi.org/10.1007/978-981-99-4370-8_9

33. González-Morales S, Solís-Gaona S, Valdés-Caballero MV, Juárez-Maldonado A, Loredo-Treviño A, Benavides-Mendoza A. Transcriptomics of biostimulation of plants under abiotic stress. Front Genet 2021;12:583888; doi: https://doi.org/10.3389/fgene.2021.583888
34. Pichyangkura R, Chadchawan S. Biostimulant activity of chitosan in horticulture. Scientia Horticulturae 2015;196:49–65; doi: https://doi.org/10.1016/j.scienta.2015.09.031
35. Pršić J, Ongena M. Elicitors of plant immunity triggered by beneficial bacteria. Front Plant Sci 2020;11:594530; doi: https://doi.org/10.3389/fpls.2020.594530
36. Nephali L, Piater LA, Dubery IA, Patterson V, Huyser J, Burgess K, *et al.* Biostimulants for plant growth and mitigation of abiotic stresses: a metabolomics perspective. Metabolites 2020;10(12):505; doi: https://doi.org/10.3390/metabo10120505
37. Pandey P, Tripathi A, Dwivedi S, Lal K, Jhang T. Deciphering the mechanisms, hormonal signaling, and potential applications of endophytic microbes to mediate stress tolerance in medicinal plants. Front Plant Sci 2023;14:1250020; doi: https://doi.org/10.3389/fpls.2023.1250020
38. Malécange M, Sergheraert R, Teulat B, Mounier E, Lothier J, Sakr S. Biostimulant properties of protein hydrolysates: recent advances and future challenges. Int J Mol Sci 2023;24(11):9714; doi: https://doi.org/10.3390/ijms24119714
39. Bonini P, Rouphael Y, Miras-Moreno B, Lee B, Cardarelli M, Erice G, *et al.* A microbial-based biostimulant enhances sweet pepper performance by metabolic reprogramming of phytohormone profile and secondary metabolism. Front Plant Sci 2020;11:567388; doi: https://doi.org/10.3389/fpls.2020.567388
40. Fouad R, Fouad H, Aziz EE, Nofal OA, Rezk AI, El-Nasharty AB, *et al.* Effect of algae and yeast on the production of essential oil and some active constituents in rosemary. Egypt Pharm J 2023;22(3):424–31; doi: https://doi.org/10.4103/epj.epj_17_23
41. Yadav P, Ansari MW, Saini S, Punia S, Kaula BC, Rani V, *et al.* Review and future prospects on the impact of abiotic stresses and tolerance strategies in medicinal and aromatic plants. Braz J Botany 2024;47(3):683–701; doi: https://doi.org/10.1007/s40415-024-01004-z
42. Esmaeil Zade NS, Sadeghi A, Moradi P. Streptomyces strains alleviate water stress and increase peppermint (Mentha piperita) yield and essential oils. Plant Soil. 2019;434(1–2):441–52; doi: https://doi.org/10.1007/s11104-018-3862-8
43. Upadhyay SK, Srivastava AK, Rajput VD, Chauhan PK, Bhojiya AA, Jain D, *et al.* Root exudates: mechanistic insight of plant growth promoting rhizobacteria for sustainable crop production. Front Microbiol 2022;13:916488; doi: https://doi.org/10.3389/fmicb.2022.916488
44. Pantigoso HA, Newberger D, Vivanco JM. The rhizosphere microbiome: plant–microbial interactions for resource acquisition. J Appl Microbiol 2022;133(5):2864–76; doi: https://doi.org/10.1111/jam.15686
45. Blanco-Vargas A, Rodríguez-Gacha LM, Sánchez-Castro N, Garzón-Jaramillo R, Pedroza-Camacho LD, Poutou-Piñales RA, *et al.* Phosphate-solubilizing *Pseudomonas* sp., and *Serratia* sp., co-culture for *Allium cepa* L. growth promotion. Heliyon. 2020;6(10):e05218: doi: https://doi.org/10.1016/j.heliyon.2020.e05218
46. Abdel-Hamid MS, Fouda A, El-Ela HKA, El-Ghamry AA, Hassan SED. Plant growth-promoting properties of bacterial endophytes isolated from roots of Thymus vulgaris L. and investigate their role as biofertilizers to enhance the essential oil contents. Biomolecular Concepts 2021;12(1):175–96; doi: https://doi.org/10.1515/bmc-2021-0019
47. Nardi S, Pizzeghello D, Schiavon M, Ertani A. Plant biostimulants: physiological responses induced by protein hydrolyzed-based products and humic substances in plant metabolism. Scientia Agricola 2016;73(1):18–23; doi: https://doi.org/10.1590/0103-9016-2015-0006
48. Moreno-Hernández JM, Mazorra-Manzano MÁ, Salazar-Leyva JA, Benítez-García I. Protein hydrolysates as biostimulants of plant growth and development. In: Biostimulants: exploring sources and applications 2022 pp. 141-175. Singapore, Singapore: Springer Nature Singapore; 2022. 141–75 pp; doi: https://doi.org/10.1007/978-981-16-7080-0_6
49. Ertani A, Nardi S, Francioso O, Pizzeghello D, Tinti A, Schiavon M. Metabolite-targeted analysis and physiological traits of *Zea mays* L. in response to application of a leonardite-humate and lignosulfonate-based products for their evaluation as potential biostimulants. Agronomy 2019;9(8):445; doi: https://doi.org/10.3390/agronomy9080445
50. Rouphael Y, Colla G. Toward a sustainable agriculture through plant biostimulants: from experimental data to practical applications. Agronomy 2020;10(10):1461; doi: https://doi.org/10.3390/agronomy10101461
51. Talaeizadeh A, Sharifi I, Alasty A, Ghatrehsamani S. Agricultural spraying drones: A comprehensive review. Smart Agricult Technol. 2025;12:101519; doi: https://doi.org/10.1016/j.atech.2025.101519
52. Rasuli N, Riahi H, Shariatmadari Z, Nohooji MG, Dehestani A, Mehrabanjoubani P. Growth enhancement, metabolic profile improvement, and DXR and TPS2 gene expression changes in Thymus vulgaris L. by cyanobacterial inoculation. J Sci Food Agriculture 2024;104(10):5751–63; doi: https://doi.org/10.1002/jsfa.13404
53. Qiu H, Su L, Wang H, Zhang Z. Chitosan elicitation of saponin accumulation in Psammosilene tunicoides hairy roots by modulating antioxidant activity, nitric oxide production and differential gene expression. Plant Physiol Biochem 2021;166:115–27; doi: https://doi.org/10.1016/j.plaphy.2021.05.033
54. Dere S. Mitigating the adverse effects of salt stress on pepper plants through arbuscular mycorrhizal fungi (AMF) and beneficial bacterial (PGPR) inoculation. Horticulturae 2024;10(11):1150; doi: https://doi.org/10.3390/horticulturae10111150
55. Wahid N, Wahab S, Iqbal S, Kanwal, Khan MN, Hayat K, et al. Biostimulants as a sustainable strategy to augment salinity tolerance in oilseed crops. In: Oilseed Crops Under Abiotic Stress: mitigation Strategies and Future Perspectives 2025 Jul 19. Singapore: Springer Nature Singapore; 2025. 1–50 pp; doi: https://doi.org/10.1007/978-981-96-8346-8_1
56. Saad Ullah M, Mahmood A, Javaid MM, Naqve M, Bibi S, Abidin ZU, *et al.* Chitosan for plant growth and stress tolerance. In: Climate-Resilient Agriculture, Vol 2: agro-Biotechnological Advancement for Crop Production. Cham: Springer International Publishing; 2023. 2, 259–80 pp; doi: https://doi.org/10.1007/978-3-031-37428-9_12
57. Han M, Kasim S, Yang Z, Deng X, Saidi NB, Uddin MK, *et al.* Plant extracts as biostimulant agents: a promising strategy for managing environmental stress in sustainable agriculture. Phyton 2024;93(9):2149; doi: https://doi.org/10.32604/phyton.2024.054009
58. Elansary HO, Mahmoud EA, El-Ansary DO, Mattar MA. Effects of water stress and modern biostimulants on growth and quality characteristics of mint. Agronomy 2019;10(1):6; doi: https://doi.org/10.3390/agronomy10010006
59. Chaski C, Giannoulis KD, Alexopoulos AA, Petropoulos SA. Biostimulant application alleviates the negative effects of deficit irrigation and improves growth performance, essential oil yield and water-use efficiency of mint crop. Agronomy 2023;13(8):2182; doi: https://doi.org/10.3390/agronomy13082182
60. Korkmaz E, Çiçek N. Investigation of the alleviating effect of liquid seaweed fertilizer on Lavandula officinalis under salt stress. Environ Monit Assessment 2024;196(2):187; doi: https://doi.org/10.1007/s10661-024-12377-9
61. Aishwath OP, Lal RA. Resilience of spices, medicinal and aromatic plants with climate change induced abiotic stresses. Ann Plant Soil Res 2016;18(2):91–109.
62. Sharma P, Kaushal S, Tandon R, Goel S, Baishya R. Plant growth promoting bacteria and arbuscular mycorrhizal fungi induced salinity tolerance in Withania somnifera (L.) Dunal. J Plant Growth Regulation 2025;44(7):4001–21; doi: https://doi.org/10.1007/s00344-025-11672-0

63. European Biostimulants Industry Council (EBIC). Promoting the biostimulant sector. 2019. Available from: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/14475-Single-market-strategy-2025/F3514738_en. EBIC Transparency Register: 034239613511-14
64. European Parliament, Council of the European Union. Regulation (EU) 2019/1009 of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003. Off J Eur Union. 2019;L170:1–114. Available from: https://eur-lex.europa.eu/eli/reg/2019/1009/oj
65. du Jardin P, Xu L, Geelen D. Agricultural functions and action mechanisms of plant biostimulants (PBs) an introduction. The chemical biology of plant biostimulants. 2020:1–30; doi: https://doi.org/10.1002/9781119357254.ch1
66. Caradonia F, Battaglia V, Righi L, Pascali G, La Torre A. Plant biostimulant regulatory framework: prospects in Europe and current situation at international level. J Plant Growth Regulation 2019;38(2):438–48; doi: https://doi.org/10.1007/s00344-018-9853-4
67. Rouphael Y, Carillo P, Cristofano F, Cardarelli M, Colla G. Effects of vegetal-versus animal-derived protein hydrolysate on sweet basil morpho-physiological and metabolic traits. Scientia Horticulturae 2021;284:110123; doi: https://doi.org/10.1016/j.scienta.2021.110123
68. Lucini L, Miras-Moreno B, Ertani A. Bioactive compounds and evaluation of biostimulant activity. In: Biostimulants for sustainable crop production 2020 Aug 10. Burleigh Dodds Science Publishing; 2020. 31–52 pp; Available from: https://www.taylorfrancis.com/books/mono/10.1201/9781003047865/biostimulants-sustainable-crop-production?refId=d350bf33-b2f0-4d52-83c4-be781a377f56&context=ubx
69. Baghdadi A, Della Lucia MC, Borella M, Bertoldo G, Ravi S, Zegada-Lizarazu W, *et al.* A dual-omics approach for profiling plant responses to biostimulant applications under controlled and field conditions. Front Plant Sci 2022;13:983772; doi: https://doi.org/10.3389/fpls.2022.983772
70. Sharma HSS, Selby C, Carmichael E, Mcroberts C, Rao JR, Ambrosino P, *et al.* Physicochemical analyses of plant biostimulant formulations and characterisation of commercial products by instrumental techniques. Chem Biol Technol Agriculture 2016;3(1):13; doi: https://doi.org/10.1186/s40538-016-0064-6
71. Zhao J, Wang M, Saroja SG, Khan IA. NMR technique and methodology in botanical health product analysis and quality control. J Pharm Biomed Anal 2022;207:114376; doi: https://doi.org/10.1016/j.jpba.2021.114376
72. Hamade K, Fliniaux O, Fontaine JX, Molinié R, Petit L, Mathiron D, *et al.* NMR and LC–MS-based metabolomics to investigate the efficacy of a commercial bio stimulant for the treatment of wheat (*Triticum aestivum*). Metabolomics 2024;20(3):58; doi: https://doi.org/10.1007/s11306-024-02131-0
73. Garg S, Nain P, Kumar A, Joshi S, Punetha H, Sharma PK, *et al.* Next generation plant biostimulants & genome sequencing strategies for sustainable agriculture development. Front Microbiol 2024;15:1439561; doi: https://doi.org/10.3389/fmicb.2024.1439561
74. Gupta S, Bhattacharyya P, Kulkarni MG, Doležal K. Growth regulators and biostimulants: upcoming opportunities. Front Plant Sci 2023;14:1209499; doi: https://doi.org/10.3389/fpls.2023.1209499
75. Markets and Markets. Biostimulants market by active ingredient (humic substances, seaweed extracts, amino acids, minerals & vitamins), crop type, mode of application (foliar treatment, soil treatment), form, and region—global forecast to 2031. Markets and Markets; 2026.
76. Fortune Business Insights. India biostimulants market size, share & industry analysis, by source, active ingredient, application, crop type, and forecast, 2025–2032. Fortune Business Insights; 2026.
77. Farruggia D, Licata M, Di Miceli G, Urso G, Salamone F, Novak J. Animal and plant-derived protein hydrolysates positively affect yield traits but produce contrasting response on chemicals of organic rosemary (Salvia rosmarinus Spenn.) grown under rainfed conditions. Italian J Agronomy 2025;20(3):100048; doi: https://doi.org/10.1016/j.ijagro.2025.100048
78. Prakhyath KM, Yogendra ND, Padalia RC, Anand KGV, Veeragurunathan V, Prasad K, et al. Seaweed extract of Solieria chordalis (C. Agardh) J. Agardh) improves growth, yield and essential oil production and economics of Patchouli (Pogostemon cablin (Blanco) Benth. J Appl Phycology 2025;37(4):2921–32; doi: https://doi.org/10.1007/s10811-025-03537-6
79. Prakhyath KM, Sharma PM, Pragadheesh VS, Gopalakrishnan VAK, Veeragurunathan V, Ghosh A, et al. Comparative evaluation of formulated and Gracilaria edulis derived seaweed extract in enhancing growth, yield, quality and economics of Artemisia pallens Wall. ex. DC. S Afr J Bot 2025;185:106–14; doi: https://doi.org/10.1016/j.sajb.2025.07.060
80. Matthews S, Siddiqui Y, Ali A. Unleashing the power of biostimulants for enhanced crop growth, productivity, and quality: a comprehensive review. J Plant Nutr 2025;48(4):703–25; doi: https://doi.org/10.1080/01904167.2024.2412736
81. Grand view research. Biostimulants market (2026-2033). 2026. Available from: https://www.grandviewresearch.com/industry-analysis/biostimulants-market
82. Demir S, Durak ED, Güneş H, Boyno G, Mulet JM, Rezaee Danesh Y, *et al.* Biological control of three fungal diseases in strawberry (Fragaria× ananassa) with arbuscular mycorrhizal fungi. Agronomy 2023;13(9):2439; doi: https://doi.org/10.3390/agronomy13092439
83. Kisiriko M, Anastasiadi M, Terry LA, Yasri A, Beale MH, Ward JL. Phenolics from medicinal and aromatic plants: characterisation and potential as biostimulants and bioprotectants. Molecules 2021;26(21):6343; doi: https://doi.org/10.3390/molecules26216343
84. Aziz ZN, Hussein AG, Kadhim ZJ. Effect of biofertilizers (Mycorrhizal fungi, Trichoderma, *Bacillus subtilis* bacteria) and seaweed extracts on the growth and yield of mint (Mentha spicata): an integrative study of vegetative growth and secondary compounds. Int J Adv Biochem Res 2025;9(5):100–6; doi: https://doi.org/10.33545/26174693.2025.v9.i5b.4302
85. Zhang X, Yin J, Ma Y, Peng Y, Fenton O, Wang W, *et al.* Unlocking the potential of biostimulants derived from organic waste and by-product sources: improving plant growth and tolerance to abiotic stresses in agriculture. Environ Technol & Innov 2024;34:103571; doi: https://doi.org/10.1016/j.eti.2024.103571
86. Calia C, González García S, Ingrao C, Lagioia G, Ruta C, Secchi N, *et al.* Life cycle assessment of microbial plant biostimulant production for application in sustainable agricultural systems. Sci Total Environ 2025;981:179610; doi: https://doi.org/10.1016/j.scitotenv.2025.179610
87. Vijay Anand KG, Eswaran K, Ghosh A. Life cycle impact assessment of a seaweed product obtained from Gracilaria edulis—a potent plant biostimulant. J Clean Prod 2018;170:1621–7; doi: https://doi.org/10.1016/j.jclepro.2017.09.241
88. Mashamaite CV, Ngcobo BL, Manyevere A, Bertling I, Fawole OA. Assessing the usefulness of Moringa oleifera leaf extract as a biostimulant to supplement synthetic fertilizers: a Review. Plants 2022;11(17):2214; doi: https://doi.org/10.3390/plants11172214
89. Torre LA, Battaglia V, Caradonia F. Legal aspects of the use of plant strengtheners (biostimulants) in Europe. Bulg J Agric Sci 2013;19:1183–9.
90. Traon, D., Amat, L., Zotz, F., and du Jardin, P. A Legal Framework for Plant Biostimulants and Agronomic Fertiliser Additives in the EU. Report to the European Commission, DG Enterprise & Industry, Arcadia International, 2014, p. 115.
91. Arinaitwe U, Yabwalo DN, Hangamaisho A. Unlocking the potential of biostimulants: a review of classification, mode of action, formulations, efficacy, mechanisms, and recommendations for sustainable intensification. Int J Plant Biol 2025;16(4):122; doi: https://doi.org/10.3390/ijpb16040122
92. Banks JM, Percival GC. Evaluation of biostimulants to control Guignardia leaf blotch (*Guignardia aesculi*) of horsechestnut

and black spot (*Diplocarpon rosae*) of roses. Arboric Urban For 2012;38(6):258–261; doi: https://doi.org/10.48044/jauf.2012.035
93. Cerdan M, Sanchez-Sanchez A, Jorda JD, Juarez M, Sanchez-Andreu J. Effect of commercial amino acids on iron nutrition of tomato plants grown under lime-induced iron deficiency. J Plant Nutr Soil Sci 2013;176:859–66; doi: https://doi.org/10.1002/jpln.201200525
94. Carvalho MEA, Castro PRDCE, Gallo LA, Ferraz MVDC Jr. Seaweed extract provides development and production of wheat. Rev Agrarian 2014;7:166–70; Available from: https://repositorio.usp.br/directbitstream/ed09be96-a98e-4c4a-8e62-f1c2933c297f/2478256-Seaweed_extract_provides_development_and_production_of_wheat.pdf
95. De Oliveira FDAD, Medeiros JFD, Oliveira MKTD, Souza AAT, Ferreira JA, Souza MS. Interaction between water salinity and biostimulant in the cowpea plants. Rev Brasil De Eng Agríc Ambien 2013;17:465–71; doi: https://doi.org/10.1590/S1415-43662013000500001
96. Rose MT, Patti AF, Little KR, Brown AL, Jackson WR, Cavagnaro TR. A meta-analysis and review of plant-growth response to humic substances: practical implications for agriculture. Adv Agronomy 2014;124:37–89; doi: https://doi.org/10.1016/B978-0-12-800138-7.00002-4
97. Raj Y, Ali N, Pati AM, Kumar R. Cleaner production technologies for the amelioration of soil health, biomass and secondary metabolites in Ocimum basilicum L. under Indian Western Himalaya. Front Plant Sci 2022;13:976295; doi: https://doi.org/10.3389/fpls.2022.976295
98. Jat RS, Basak BB, Gajbhiye NA. Organic manures and biostimulants fostered soil health and increased the harvest quality of the medicinal herb ashwagandha. Agronomy J 2021;113(1):504–514; doi: https://doi.org/10.1002/agj2.20457
99. Song P, Deng Y, Yu Y, Zhang L, Liu Y. Plant Growth-Promoting Microorganisms Mediate Plant Metabolic Reprogramming to Manage the Rhizospheric Microbiome. Microorganisms 2026;14(3):578; doi: https://doi.org/10.3390/microorganisms14030578
100. Mazeed A, Maurya P, Kumar D, Suryavanshi P. The enhancement of root yield and quality of ashwagandha Withania somnifera (L.) Dunal by weeds leaves extracts. Indian J Weed Sci 2022;54(1):81–6.
101. Ciriello M, Formisano L, El-Nakhel C, Corrado G, Rouphael Y. Biostimulatory action of a plant-derived protein hydrolysate on morphological traits, photosynthetic parameters, and mineral composition of two basil cultivars grown hydroponically under variable electrical conductivity. Horticulturae 2022;8(5):409; doi: https://doi.org/10.3390/horticulturae8050409
102. Di Mola I, Conti S, Cozzolino E, Melchionna G, Ottaiano L, Testa A, *et al.* Plant-based protein hydrolysate improves salinity tolerance in hemp: agronomical and physiological aspects. Agronomy 2021;11(2):342; doi: https://doi.org/10.3390/agronomy11020342
103. El-Hefny M, Hussien MK. Enhancing the growth and essential oil components of Lavandula latifolia using Malva parviflora extract and humic acid as biostimulants in a field experiment. Scientific Rep 2025;15(1):774; doi: https://doi.org/10.1038/s41598-024-82127-x
104. Pirani H, Ebadi MT, Rezaei A. Effect of seaweed fertilizer foliar application on growth parameters, yield, and essential oil content and composition of hyssop (Hyssopus officinalis L.). Iranian J MedAromatic Plants Res 2020;36(3):376–89; doi: https://doi.org/10.22092/ijmapr.2020.128252.2660
105. El Sherif F, Albotnoor N, Yap YK, Meligy A, Khattab S. Enhanced bioactive compounds composition in Lavandula officinalis in-vitro plantlets using NaCl and Moringa oleifera, Aloe vera and Spirulina platensis extracts. Ind Crops Prod 2020;157:112890; doi: https://doi.org/10.1016/j.indcrop.2020.112890
106. Mehmood A, Naveed K, Ayub Q, Alamri S, Siddiqui MH, Wu C, *et al.* Exploring the potential of moringa leaf extract as bio stimulant for improving yield and quality of black cumin oil. Scientific Rep 2021;11(1):24217; doi: https://doi.org/10.1038/s41598-021-03617-w
107. Oueslati S, Ellouzi H, Zorrig W, Debez A, Abdelly C, Hanana M. Benefits of natural biostimulants: ginger and moringa extracts as seed priming agents to improve salinity tolerance of Ocimum basilicum L. Notulae Botanicae Horti Agrobotanici Cluj-Napoca 2025;53(4):14869; doi: https://doi.org/10.15835/nbha53414869
108. Prakhyath KM, Yogendra ND, Arul Prakash T, Padalia RC, Veeragurunathan V, Gopalakrishnan VAK, *et al.* Seaweed sap from Solieria chordalis enhances growth, yield and essential oil quality in rose-scented geranium (Pelargonium graveolens L'Hér.) varieties. Biochem Systematics Ecol 2025;123:105062; doi: https://doi.org/10.1016/j.bse.2025.105062
109. Vongnhay V, Shukla MR, Ayyanath MM, Sriskantharajah K, Saxena PK. In vitro morphogenesis of tobacco: modulation of endogenous growth regulators by Tulsi (Holy Basil). Plants 2024;13(14):2002; doi: https://doi.org/10.3390/plants13142002
110. Yogendra ND, Prakhyath KM, Padalia RC, Ghosh A. Application of seaweed liquid extract improves the growth, yield, and chemical constituents of lemongrass. J Plant Nutr 2024;47(19):3571–84; doi: https://doi.org/10.1080/01904167.2024.2380777
111. Yogendra ND, Prakhyath KM, Ravikumara R, Padalia RC, Ghosh A. Effect of Kappaphycus alvarezii seaweed liquid extract on growth, yield and chemical constituents of Geranium (Pelargonium graveolens l'Herit. ex Aiton). J Plant Nutr 2025;48(6):907–20; doi: https://doi.org/10.1080/01904167.2024.2415478
112. Ali EF, Hassan FAS, Elgimabi M. Improving the growth, yield and volatile oil content of Pelargonium graveolens L. Herit by foliar application with moringa leaf extract through motivating physiological and biochemical parameters. South Afr J Botany 2018;119:383–9; doi: https://doi.org/10.1016/j.sajb.2018.10.003
113. Basak BB, Saha A, Gajbhiye NA, Manivel P. Potential of organic nutrient sources for improving yield and bioactive principle of ashwagandha (Withania somnifera) through enhanced soil fertility and biological functions. Commun Soil Sci Plant Anal 2020;51(6):779–93; doi: https://doi.org/10.1080/00103624.2020.1729368
114. Basak BB, Jat RS, Gajbhiye NA, Saha A, Manivel P. Organic nutrient management through manures, microbes and biodynamic preparation improves yield and quality of Kalmegh (Andrographis paniculata), and soil properties. J Plant Nutr 2020;43(4):548–62; doi: https://doi.org/10.1080/01904167.2019.1685100
115. Giordano M, El-Nakhel C, Caruso G, Cozzolino E, De Pascale S, Kyriacou MC, *et al.* Stand-alone and combinatorial effects of plant-based biostimulants on the production and leaf quality of perennial wall rocket. Plants 2020;9(7):922; doi: https://doi.org/10.3390/plants9070922
116. Chrysargyris A, Skaltsa H, Konstantopoulou M. Medicinal and aromatic plants (MAPs): the connection between cultivation practices and biological properties. Agronomy 2022;12(12):3108; doi: https://doi.org/10.3390/agronomy12123108
117. Amato G, Cardone L, Cicco N, Denora M, Perniola M, Casiello D, *et al.* Morphological traits, yield, antioxidant activity and essential oil composition of oregano as affected by biostimulant foliar applications. Ind Crops Prod 2024;222:119702 doi: https://doi.org/10.1016/j.indcrop.2024.119702
118. Slovenian Institute for Standardization (SIST). SIST EN 17701-2:2025. Plant biostimulants—Determination of specific elements—Part 2: Determination of total content of Cd, Pb, Ni, As, Cr, Cu and Zn. Ljubljana: SIST; 2025.

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