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A Comprehensive Review on Biostimulants for Sustainable Agriculture: Global Market Trends and Experimental Challenges

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ABSTRACT

Biostimulants are natural or man-made substances that help plants grow better without acting as plant food or pesticides. According to the European Biostimulants Industry Council and EU rules, biostimulants help plants use nutrients more efficiently, cope with difficult growing conditions, and produce better crops by activating certain plant functions. Unlike biofertilizers, which add nutrients through living microbes, biostimulants help control plant growth and the way plants interact with helpful microbes. Main types of biostimulants include enzyme products, beneficial

microbes (such as fungi and bacteria that improve growth), soil-derived natural acids, digested proteins, amino acids, and extracts from plants or seaweed. These products help roots grow, improve nutrient uptake, balance water in the plant, and protect plants from stress. As climate change, damaged soil, and the need for sustainable farming become more serious, biostimulants offer a way to use fewer chemical fertilizers, strengthen crops, and protect the environment. The worldwide biostimulants market was worth about USD 3.0 billion in 2022 and may grow to USD 5.4–6.85 billion by 2027–2030, especially for products with microbes and liquids. Europe uses biostimulants the most, but use is growing rapidly in Asia–Pacific, with India as a particularly large and expanding market. Even though there are still challenges with rules, testing, and quality, biostimulants are an important tool for sustainable farming and food security.

INTRODUCTION

The increasingly interconnected global economy continues to amplify the role of agricultural systems in supporting human populations. With the global population now exceeding 8 billion and economic development accelerating, the demand for essential commodities, particularly food, fiber, and biofuels, has risen markedly (OECD/FAO 2024)(Anderson 2023) . However, the finite availability of arable land presents a growing constraint. To meet these demands, agriculture has intensified, especially through the widespread adoption of synthetic fertilizers, raising significant environmental concerns. Agricultural productivity and crop quality are increasingly constrained worldwide by climatic changes and adverse local conditions. Environmental stressors such as elevated atmospheric CO_2 levels, global warming, soil salinization, desertification, and nutrient imbalances caused by mineral toxicities or deficiencies negatively affect plant growth, development, yield, and product quality. In severe cases, these factors have led to species decline and localized extinction. Empirical evidence demonstrates that abiotic stressors are responsible for yield reductions exceeding 50% in most major crops (Sharma 2024; Arif et al. 2025; Baars et al. 2023; Jan et al. 2025; Hussain et al. 2023; Mandal et al. 2023; Kopecká et al. 2023). For instance, rice (Oryza sativa) yields declined by 15% for every 1 °C increase in temperature between 1979 and 2003 (Impa et al. 2021). Additionally, climate variability intensifies plant susceptibility to pathogens, compounding unfavorable growing conditions (Kumar et al. 2023)(Jing et al. 2024)(Wang et al. 2018). Concurrently, urbanization and climate-driven land degradation continue to reduce the availability of arable land, posing further risks to global food security in a world where food production must be doubled by 2050 to meet population demands (Seifollahi-Aghmiuni et al. 2022; Bununu et al. 2023; Ranjithkumar 2025).

In response to these pressures, the Green Revolution and later agricultural intensification have depended heavily on synthetic fertilizers and pesticides. Yet nutrient uptake efficiency is low: only 10–20% of nutrients are absorbed by plants, and as little as 0.1% of pesticides reach their intended targets. Most of these chemicals cause environmental contamination, disrupt soil microbial communities, and pollute water bodies (Thwaites et al. 2025; Daszkiewicz 2022; Saleem et al. 2024; FAO et al. 2021; Ansari et al. 2024; Meena et al. 2020; Bhardwaj et al. 2022). Given these issues, reducing chemical input is crucial for sustainable agriculture. Biostimulants (BSs) offer promising alternatives because they are bioactive, non-toxic to non-target organisms, and do not persist in the environment (Dubey & Misra 2025; Rouphael& Colla 2020). Incorporating biostimulants into modern crop management shows a growing focus on environmentally responsible approaches that balance efficiency with sustainability. BSs play multiple roles in nutrient dynamics, stress adaptation, and microbial interactions, making them important tools for resilient, productive agriculture (Rouphael& Colla 2020; Khoulati et al. 2025). Research on the use of biostimulants in agriculture is still new, but their potential is considerable. By studying how they work, scientists can find ways to optimize their use (Baltazar et al. 2021; Roche et al. 2024; Bhupenchandra et al. 2022; Johnson et al. 2024). In recent years, studies in plant science have provided strong evidence for the role of biostimulants in boosting crop productivity and resilience. Therefore, this review covers the different types and functions of biostimulants and highlights experimental challenges, market potential, and sustainability concerns.

METHODOLOGY

Data source and search strategy

In this study, we used the Scopus database to collect articles on biostimulants and sustainable agriculture, with data collected on January 12, 2026. We then analyzed the information, as shown in Fig. 2. The search terms included words like "biostimulant," "biofertilizer," "plant growth promoter," and "microbial inoculant" as well as phrases such as "sustainable agriculture," "sustainable farming," "agricultural sustainability," "eco-friendly agriculture," and "environmentally friendly farming." Articles published between 2015 and 2025 were included. We collected information about the articles, their authors, countries, institutions, journals, keywords, and citations.

Inclusion and Exclusion Criteria

To ensure consistency and focus, we included only documents labeled as 'articles.' This way, we prioritized original research, which usually gives clear methods and main data. We manually reviewed the most cited articles on the topic to ensure we did not miss any important works. Reviewing papers, book chapters, short surveys, notes, books, and retracted papers was omitted because they may not include sufficient data or a full review. Still, we checked that omitting these types did not omit any major contributions to our study.

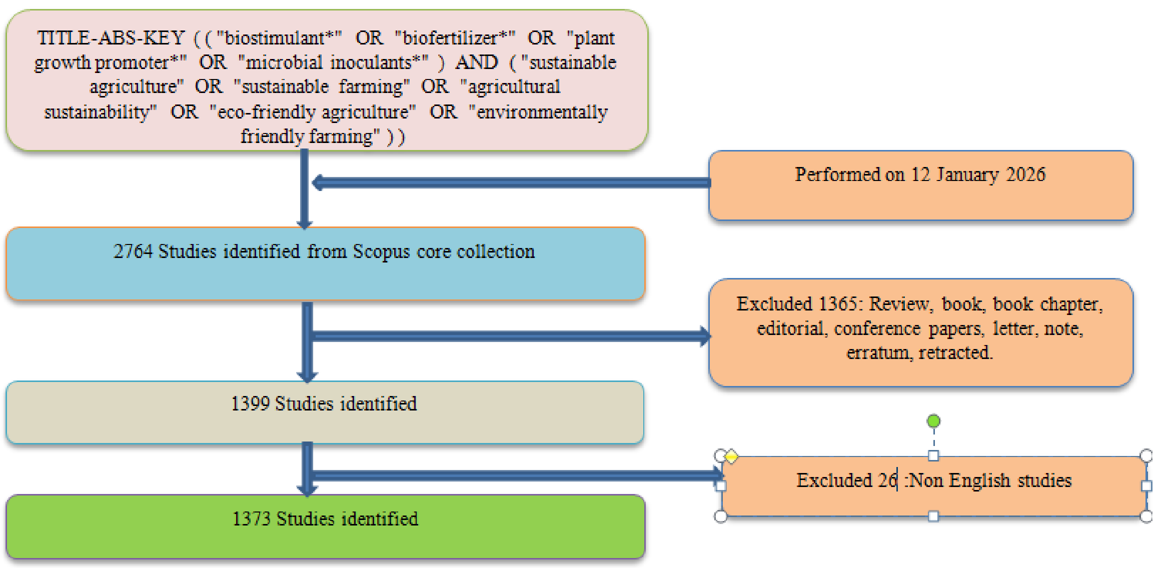


Fig.1. Strategy for data retrieval and collection

Research trends on biostimulants for sustainable agriculture

We assess annual research growth by reviewing the publication years of relevant articles. Figure 3 shows the distribution of articles published between 2015 and 2025. The results indicate increased researcher interest in biostimulants for sustainable agriculture. A search of electronic databases yielded 2,764 records. After excluding 1,391 entries according to the study's exclusion criteria, 1,373 articles were considered for further analysis.

The trend toward more academic research output has clear reasons. It has helped develop practical approaches to the use of biostimulants in sustainable agriculture. The increase in research activity has led to real achievements, enabling sustainable solutions in agriculture.

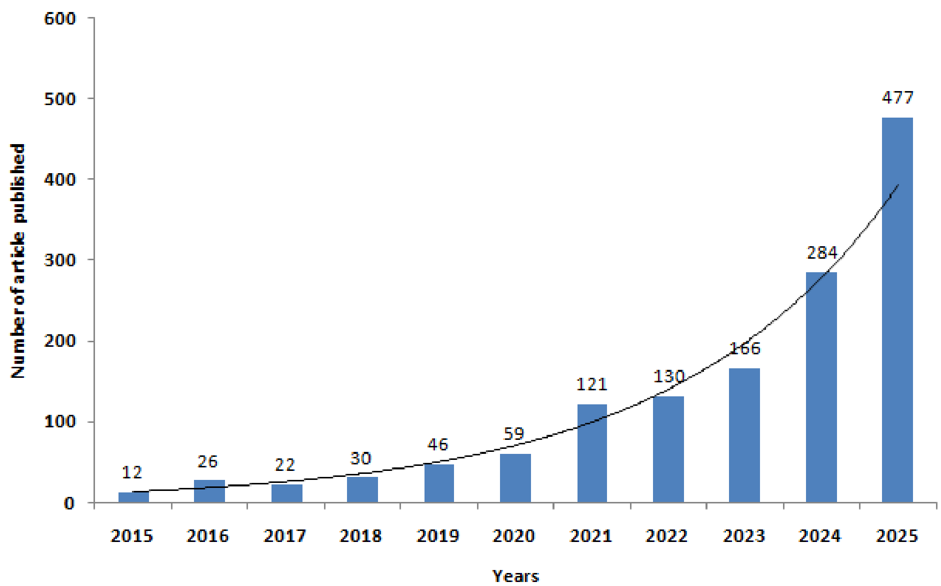


Fig.2. Publication trend in the number of articles related to biostimulants for sustainable agriculture in the past decade.

Subject area distribution

A total of 1373 articles were distributed across 25 subject categories. The largest proportion of publications was in Agricultural and Biological Sciences (39%)**,** followed by Environmental Science (15%), Biochemistry, Genetics and Molecular Biology (12%)**,** and Immunology and Microbiology (8%) (Fig. **4).**

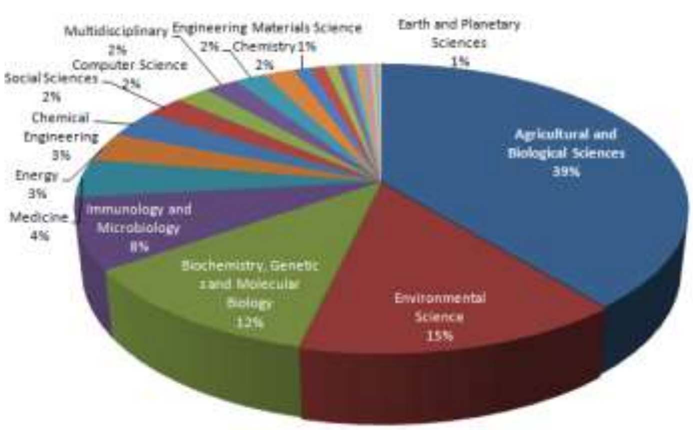


Fig. 4 Subject-wise distribution of articles related to biostimulants for sustainable agriculture in the past decade.

Most productive countries

As shown in Fig. 5, 1373 selected publications originated from 110countries and regions, with the top 10 countries participating in biostimulants for sustainable agriculture. India led with 272publications, followed by Italy with 155, China with 144, the USA with 86, and Brazil with 79.**Fig.5**presents an analysis of co-authored papers by scholars from different countries on biostimulants for sustainable agriculture. The data indicate that China has contributed a comparatively higher number of co-authored publications in this field. Publications from China, the USA, and Italy represent over 40% of the total articles published.

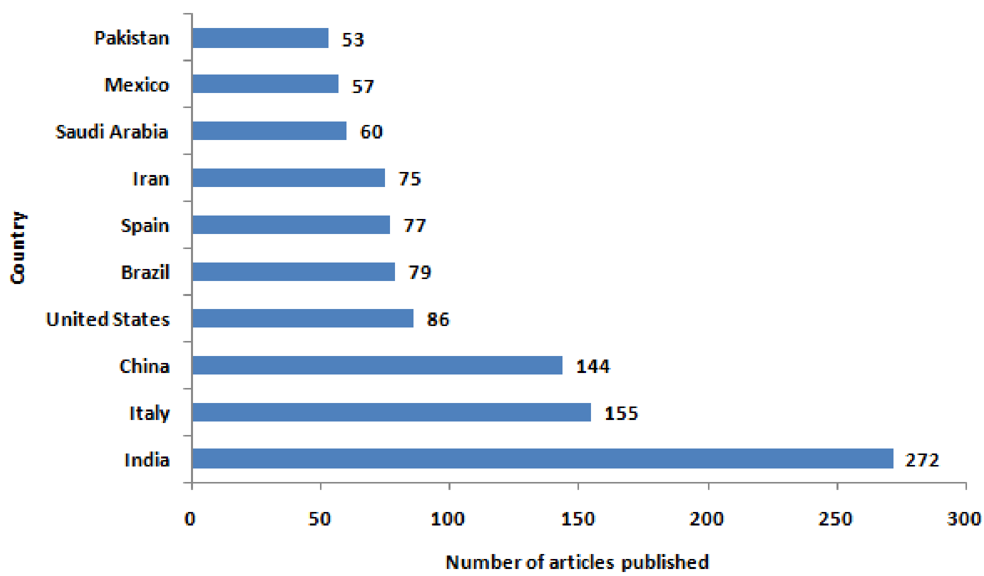
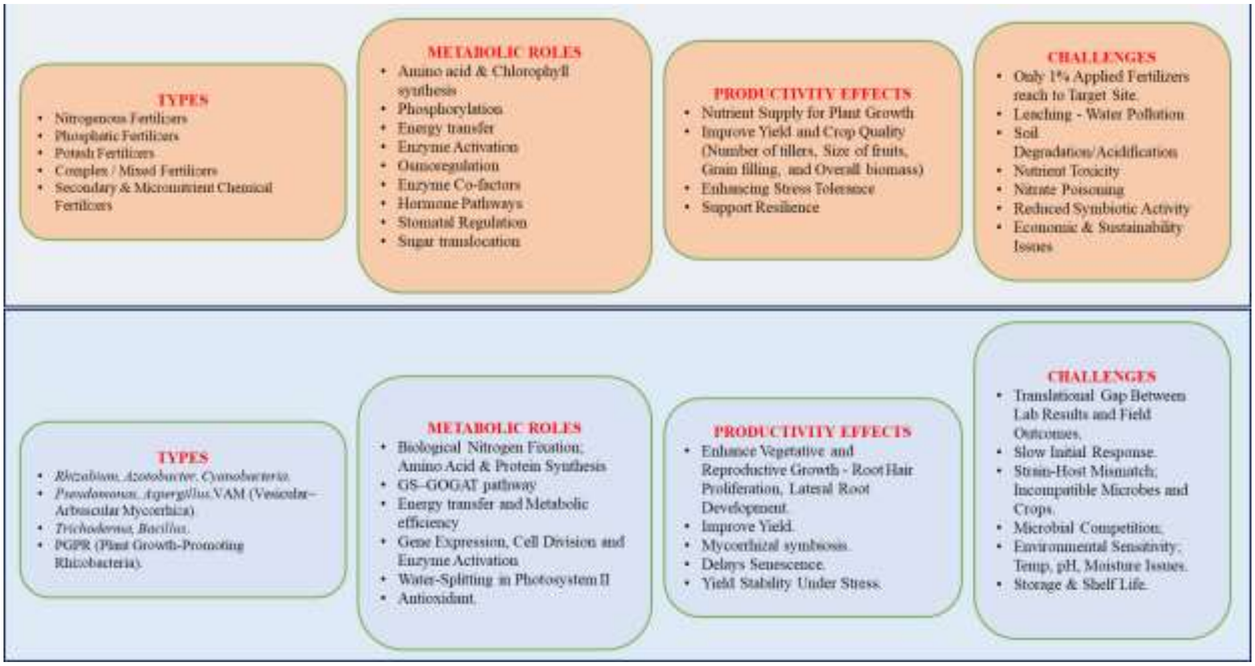


Fig. 5: The top 10 countries publishing the highest number of articles

Biostimulants: A solution to mitigate agricultural problems

In recent years, modern agricultural systems have encountered the complex challenge of simultaneously addressing global food security and the imperative for sustainable farming practices. On the one hand, there is an increasing need to adopt highly efficient agricultural solutions that boost crop productivity to meet the growing demands of a rapidly expanding population. On the other hand, agricultural methods must align with eco-friendly principles that prioritize environmental conservation and human health. To intensify agriculture, the widespread application of mineral fertilizers and agrochemicals has become common. However, the long-term and excessive use of these chemical inputs has led to multiple adverse consequences, including soil degradation, decreased crop yield over time, and pollution of air, water, and land ecosystems (Selvan et al. 2023)(Gomiero et al. 2011). These effects raise significant concerns regarding environmental sustainability and human well-being. As a response, the use of bio-based products, such as biostimulants and biofertilizers, has emerged as a promising strategy to increase crop yields, improve nutrient uptake, reduce abiotic stress, and align agricultural production with both productivity and sustainability objectives. These bio-products are derived from natural sources and differ fundamentally from conventional soil conditioners in their origin, composition, and biological activity. Both biostimulants and biofertilizers are non-toxic to plants, soil, and consumers, and are considered safer alternatives to traditional chemical inputs. Compared with biofertilizers, which supply nutrients through active microbial processes (e.g., nitrogen fixation, phosphate solubilization), biostimulants primarily modulate plant physiology and rhizosphere interactions without acting as direct nutrient sources (Calvo et al. 2014)(Rouphael& Colla 2020)(Rouphael& Colla 2020)(Bhupenchandra et al. 2020).

Biostimulants are a heterogeneous group of natural or synthetic inputs that enhance plant performance by stimulating intrinsic biological processes rather than supplying nutrients directly. They improve nutrient uptake and use efficiency, bolster tolerance to abiotic stresses (e.g., drought, salinity, heat), and can elevate crop quality while supporting more sustainable production systems (Bhupenchandra et al. 2020)(Du Jardin 2015). The European Biostimulants Industry Council (EBIC, 2016) defines them as substances and/or microorganisms that, when applied to plants or the rhizosphere, stimulate natural processes to improve nutrient uptake, nutrient use efficiency, tolerance to abiotic stress, and crop quality. In a regulatory context, European Regulation (EU) 2019/1009 classifies plant biostimulants as products that stimulate nutritional processes independently of the nutrients they contain, with four primary objectives: (i) enhancing nutrient use efficiency, (ii) increasing abiotic stress tolerance, (iii) improving qualitative traits, and (iv) increasing availability of nutrients in the soil/rhizosphere (Yakhin et al. 2017)(Papnai et al. 2022)(Dubey & Sharma 2023). The regulation also outlines a broad range of substances and organisms that qualify as plant biostimulants. These include humic substances, protein hydrolysates and amino acid-based products, extracts derived from macro- and microalgae and plants, silicon-based products, and a variety of beneficial microorganisms. Notably, microbial categories include Arbuscular Mycorrhizal Fungi (AMF) and Plant Growth-Promoting Rhizobacteria (PGPR), particularly species from the genera *Azotobacter*, *Azospirillum*, and *Rhizobium* (Sible et al. 2025)(Yakhin et al. 2017)(Delaeter et al. 2024)(Chabili et al. 2024).



Fig, 6 Types, metabolic roles, productivity effects and challenges of chemical and biological fertilizers.

The performance of plant biostimulants often varies considerably depending on the **crop species,** soil characteristics, and prevailing climatic conditions. Different plant species and cultivars respond differently to biostimulant applications due to variations in physiological traits, nutrient requirements, and metabolic pathways. Similarly, soil properties such as pH, organic matter content, nutrient availability, and microbial activity can influence the effectiveness of biostimulant formulations. Environmental factors, including temperature, rainfall patterns, and water availability, also play a critical role in determining plant responses. Consequently, the beneficial effects observed in one cropping system or agroecological region may not necessarily be replicated under different environmental conditions.

In addition to environmental variability, the literature also reports inconsistent findings regarding yield improvement and stress tolerance associated with biostimulant use. While numerous studies demonstrate enhanced crop productivity and improved tolerance to stresses such as drought, salinity, and nutrient deficiency, other investigations report only marginal or inconsistent benefits. These discrepancies may arise from differences in experimental conditions, biostimulant composition, application methods, and crop management practices. Such variability highlights the need for more systematic and well-controlled studies to better understand the conditions under which biostimulants provide reliable agronomic benefits and to develop optimized application strategies for different cropping systems.

Types of biostimulants

Biostimulants encompass a broad spectrum of biologically active compounds and organisms that enhance plant growth, nutrient acquisition, and stress resilience. These include both enzyme-based and microorganism-based categories, each functioning through distinct mechanisms to support plant development and soil health.

Microbial biostimulants

Mycorrhizal Fungi,notably those belonging to the *Glomus* genus, form mutualistic associations with plant roots. These fungi effectively extend the plant's root system, thereby enhancing the uptake of essential nutrients, including phosphorus, nitrogen, and various micronutrients. Additionally, they support water absorption, improve resistance to soil-borne pathogens, and bolster plant performance under stressful conditions, such as drought or nutrient-poor soils. Common genera used in biostimulants include *Glomus*, *Rhizophagus*, and *Gigaspora*(Sun et al. 2024; Seymen et al. 2021).

Plant Growth-Promoting Rhizobacteria (PGPR) offer several agronomic benefits. They fix atmospheric nitrogen, solubilize nutrients (phosphorus), synthesize plant growth hormones (auxins), and act as biocontrol agents against pathogens. These bacteria can be applied directly to the soil or root zone. Noteworthy examples include *Azospirillum* sp. and *Pseudomonas,* which enhance nitrogen fixation; *Pseudomonas fluorescens*, known for promoting plant growth and suppressing disease; and *Bacillus* sp., recognized for nutrient solubilization and pathogen resistance. *Bacillus subtilis* and *Bacillus amyloliquefaciens* are integral components of biostimulants due to their multifunctional roles. These bacteria produce enzymes that decompose organic matter, stimulate root development, and enhance nutrient uptake. Moreover, they serve as potent biocontrol agents, offering protection against various biotic stresses while also supporting plant resistance to abiotic stress factors (Khoso et al. 2024)(Ehinmitan et al. 2024)(Chandran et al. 2021). Together, these enzymes and microbial agents work synergistically with plant systems, amplifying innate biological capabilities related to growth, nutrient absorption, and environmental stress tolerance-thereby fulfilling the core objectives of biostimulant applications (Sun et al. 2024). Microbe-based biostimulants play a significant role in plant growth, health, and productivity through metabolic activities. These microorganisms fix atmospheric nitrogen, solubilize insoluble phosphates, and produce Plant Growth Regulators such as auxins, gibberellins, and cytokinins, thereby improving nutrient availability and promoting root development. Microbial inoculants significantly improve crop performance across diverse environmental conditions by facilitating nutrient acquisition and boosting overall plant vigour. In addition to their nutritional roles, many beneficial microbes induce systemic resistance in plants, giving protection against a wide range of abiotic and biotic stressors like drought, salinity, and pathogenic infections (Bashan et al. 2013)(Kumar et al. 2025). Recent advances in next-generation sequencing (NGS) and functional genomics have further enabled the development of efficient, targeted microbial inoculants adapted to specific crops and soil environments. Microbial biostimulants increase crop productivity by 16-22% on average, with Arbuscular Mycorrhizal Fungi (AMF) contributing 16-20% gains in cereals, and seed treatments boosting yields up to 21%. Co-inoculation with organic fertilizers can further increase productivity to nearly 30 %, highlighting their synergistic potential in sustainable agriculture (Kumar et al. 2025)(Morcillo et al. 2022)(Lehmann &Rillig2015)(Singh et al. 2024). Use of mixed microbial inoculants, such as plant growth-promoting rhizobacteria (PGPR), fungi, and Rhizobium spp., has resulted in an average yield increase of 22% across various crops (Nath Bhowmik & Das 2018). Biological seed treatments using microbial inoculants have also been widely studied and showed an average 21% yield increase, along with improved germination rates and seedling vigour (Sharma & Borah, 2021). AMF-based biostimulants have demonstrated remarkable effects, with an average 16% increase in cereal grain yields, influenced by soil pH and native AMF populations. Similarly, in wheat, AMF inoculation increases grain yield by up to 20% and improves harvest index by 25%, particularly under low-phosphorus conditions (Pellegrino et al. 2015). Furthermore, co-inoculation of microorganisms with organic compost has shown synergistic effects in Phaseolus vulgaris, resulting in yield increases of up to 29%, surpassing single-treatment applications (Ahmad et al. 2022). These microbial solutions provide a sustainable, eco-friendly alternative to chemical fertilizers and pesticides, supporting the transition toward more resilient, environmentally responsible agricultural systems.

Seaweed extracts

Seaweed extracts are rich in biologically active compounds, including vitamins, minerals, amino acids, and natural plant hormones, which together promote plant growth, development, and overall health. Among these, auxins and cytokinins play a key role by enhancing seed germination, stimulating root development, and improving plant vigour in many crop species. The synergistic action of natural compounds contained in marine plant extracts supports balanced vegetative and reproductive growth and increases the plant's resilience to abiotic and biotic stresses in both controlled and field conditions. Under suboptimal conditions, such as water stress, plant extract-based biostimulant treatments combined with amino acids or yeast extracts increased maize yields by 8.5-20%, highlighting their role in mitigating stress (Kumar et al. 2024). Multi-component biostimulant formulations containing plant extracts also increased tomato productivity by 39-57%, depending on irrigation levels (Patanè et al. 2025). Recent advancements in formulation technologies have led to the development of innovative biostimulant products that combine seaweed extracts with other bioactive components to maximize efficacy and broaden their applications in modern agriculture (Patanè et al. 2025; Kumar et al. 2025). These multifunctional formulations not only enhance crop performance but also align with sustainable farming practices, offering environmentally friendly alternatives to chemical-based fertilizers.

Humic and fulvic substances

Humic and fulvic acids- play an important role in plant physiology and plant-soil interactions. It influences root system architecture by stimulating lateral root initiation and root hair development, thereby increasing the plant's absorptive surface area. In addition, they affect membrane transport processes, including ion channel activity and proton pump regulation, and improve the uptake and translocation of essential nutrients (Canellas et al. 2015). By enhancing cation exchange capacity and chelating micronutrients, humic and fulvic acids substantially improve nutrient solubility and bioavailability, thereby enabling more efficient nutrient acquisition across diverse soil conditions. Biostimulants based on humic and fulvic acids improve the fertilization efficacy of essential nutrients such as Potassium, Nitrogen, and Phosphorus. These compounds also play a vital role in soils by facilitating the mobilization of minerals/elements such as iron, zinc, copper, and manganese, thereby increasing their availability to plants and enhancing water and nutrient retention (Akıncı 2011). Numerous studies have highlighted the beneficial effects of integrating humic and fulvic acids to sustain soil quality and crop yield. Haider et al. (2017) reported that increasing pod weight with soil supplemented with Humic Acid at rates of 10, 20, and 30 kg/ha resulted in high yield (Haider et al. 2017). Another study performed on tomatoes showed an increase in total yield up to 10-15 % by applying a nutrient mixture and biostimulants as foliar and soil application (Mallick et al. 2024). Pillajo et al. (2024) indicated that to lower fertilization rates in Solanum *lycopersicum* production while preserving growth and appropriate nutrition, humic compounds may be a viable substitute. Pillajo et al. (2024) suggested that humic acid could serve as a fruitful alternative for reducing fertilization rates in tomato production while maintaining optimal growth and nutrient status (Pillajo et al. 2024). Taey et al. (2019 reported the highest head weight and more yield achieved with the combined application of biofertilizer (20 g/L) and humic acid (10 mL/L), compared to the use of biofertilizer alone in Brassica oleracea (Al-Taey et al. 2019). Similarly, Dawood et al. (2019) reported that applying different levels of Humic Acid (0% to 5%) to Vicia faba resulted in higher seed yields than the control (Dawood et al. 2019).

Protein hydrolysates and amino-acid based biostimulants

Protein hydrolysates and amino acid–based biostimulants affect plant growth and stress adaptation by modulating nitrogen metabolism and stimulating the activity of key enzymes such as nitrate reductase and glutamine synthetase, thereby improving nitrogen assimilation and protein synthesis. Amino acids also act as osmoprotectants, helping plants maintain cellular homeostasis under abiotic stress conditions such as drought, salinity, and temperature extremes. Furthermore, many amino acids act as signaling molecules that activate antioxidant defense systems, enhancing the scavenging of reactive oxygen species (ROS) and protecting cellular structures from oxidative damage (Colla et al. 2017)(Calvo et al. 2014). Amino acids and peptides, derived from protein hydrolysis, play a vital role in plant growth, development, and stress management through physiological and biochemical mechanisms. These compounds also increase nutrient uptake, improve photosynthetic efficiency, and strengthen plants' resilience to various environmental stresses, such as osmoprotectants and signaling molecules. Amino acids and peptides-based biostimulants are deeply integrated into nitrogen and sulfur metabolism, acting as essential precursors for the biosynthesis of enzymes, chlorophyll, and other metabolites that regulate plant metabolic activity (Heidarzadeh 2025; Khoulati et al. 2025). Tamburino et al. (2023) evaluated several enzyme molecules, including chitinase, xylanase, and β-glucosidase as biostimulants in Lactuca sativa and reported that cell biomass increases of up to 50% and 40% for xylanase at concentrations of 0.1 and 0.01 μM, respectively, and 60 % and 30% for β-glucosidase at the same concentrations in vitro cell culture systems (Tamburino et al. 2023).

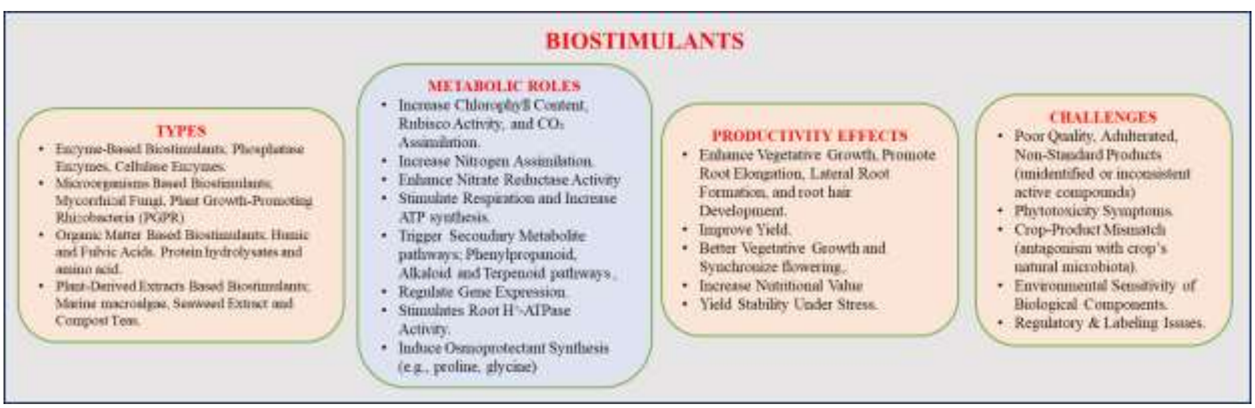
Plant-derived compounds and other emerging biostimulants

Seaweed and higher-plant extracts represent another important class of biostimulants, as they provide complex mixtures of bioactive compounds, including polysaccharides, betaines, and phenolic compounds. These molecules modulate plant signaling pathways, enhance nutrient uptake efficiency, and strengthen plant responses to abiotic and biotic stresses.Compost tea contain a variety of microbial species, which can be included under microbial inoculants, even though their composition includes proteins, amino acids, and humic substances as well (Villa et al. 2024; Ali et al. 2021; Han et al. 2024).

Enzyme-Based biostimulants

Phosphatase Enzymes, particularly phytases, play a pivotal role in liberating phosphorus from organic compounds within the soil. Since phosphorus is a critical macronutrient and often a limiting factor for crop productivity, these enzymes improve its bioavailability by breaking down organic phosphorus into inorganic phosphate forms that plants can readily absorb. Fungi, such as Aspergillus, and bacteria, such as Bacillus, are known producers of phytase and are commonly used in enzyme-based biostimulant formulations.

Cellulase Enzymes,Cellulases catalyze the breakdown of cellulose found in plant residues and organic matter. This enzymatic action enhances nutrient cycling and soil structure, while also promoting microbial activity within the rhizosphere. As a result, nutrient availability to plants improves. Fungi *Trichoderma* species and bacteria *Bacillus subtilis* are capable of producing cellulase enzymes and are frequently incorporated into biostimulant products for these purposes (Rouphael& Colla 2020)(Rouphael& Colla 2020)(Zamljen et al. 2023)(Tamburino et al. 2023). Amino acids and peptides, derived from protein hydrolysis, play a vital role in plant growth, development, and stress management. These compounds also increase nutrient uptake, improve photosynthetic efficiency, and strengthen plants' resilience to various environmental stresses as osmoprotectants and signaling molecules. Amino acids and peptides-based biostimulants are functionally aligned into nitrogen and sulphur metabolism, acting as essential precursors for the biosynthesis of enzymes, chlorophyll, and other metabolites that regulate plant metabolic activity (Phooi et al. 2022), Tamburino et al. (2023) evaluated several enzyme molecules, including chitinase, xylanase, and β-glucosidase as biostimulants in Lactuca sativa and reported that cell biomass increases of up to 50% and 40% for xylanase at concentrations of 0.1 and 0.01 μM, respectively, and 60% and 30 % for β-glucosidase at the same concentrations in vitro cell culture systems (Tamburino et al. 2023). Patanè et al. (2025) reported productivity increases of 57% under no irrigation stress and 39% under full irrigation in Solanum lycopersicum, averaged across enzyme-based bio stimulant treatments compared with the control (Bashir et al. 2025. In agriculture, they are generally applied through foliar sprays or soil amendments, resulting in improved plant growth, yield, and quality in many crop species. Recent research emphasizes biotechnological innovations to optimize their production, formulation, and delivery, such as enzymatic hydrolysis, fermentation technologies, and nano-formulations to maximize their effectiveness. Importantly, the use of amino acid and peptide-based bio stimulants supports sustainable farming practices by reducing dependence on chemical fertilizers and pesticides, aligning agricultural productivity (Ranasingha et al. 2024)(Khoulati et al. 2025)(Sun et al. 2024).



Fig, 7 Major types, metabolic roles, productivity effects and challenges of biostimulants.

Mechanism of action of biostimulants

Plant biostimulants help plants grow and cope with stress by affecting their metabolism, nutrient uptake, and interactions with microbes. One main way they work is by changing hormone signals, especially those involving auxins, cytokinins, and gibberellins. Many biostimulants, such as seaweed extracts and microbial products, either contain hormone-like substances or encourage plants to make more hormones. This leads to more cell division, cell growth, and overall plant development. Auxin-like effects help roots branch out and grow longer. Cytokinins promote shoot growth and delay leaf aging. Gibberellins help stems grow, and seeds sprout, thereby making plants stronger and more productive. Biostimulants also help plants take up and transport nutrients by increasing the activity of certain root transport proteins and activating genes that control nutrient movement. As a result, plants absorb more essential nutrients, such as nitrogen, phosphorus, potassium, and iron. Some biostimulants also boost the activity of enzymes that help plants use these nutrients, making them more efficient and less dependent on chemical fertilizers.

Biostimulants also shape how roots grow and interact with the soil, which is important for plant health and how nutrients move in the soil. Using humic substances, protein hydrolysates, and microbial biostimulants can help roots branch out, grow more root hairs, and increase total root mass. These changes give roots more surface area to take in water and nutrients, and they also help plants handle tough conditions like drought and salty soils.

Another important way biostimulants work is by helping plants interact with helpful microbes. Microorganisms, such as plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, make nutrients more readily available to plants. They also produce substances that help plants grow and make plants more resistant to stress. These microbes live around plant roots or inside plant tissues and send signals that control plant defenses and metabolism. By working together in these ways, biostimulants help plants grow better, handle stress, and support more sustainable farming (Fig.8).

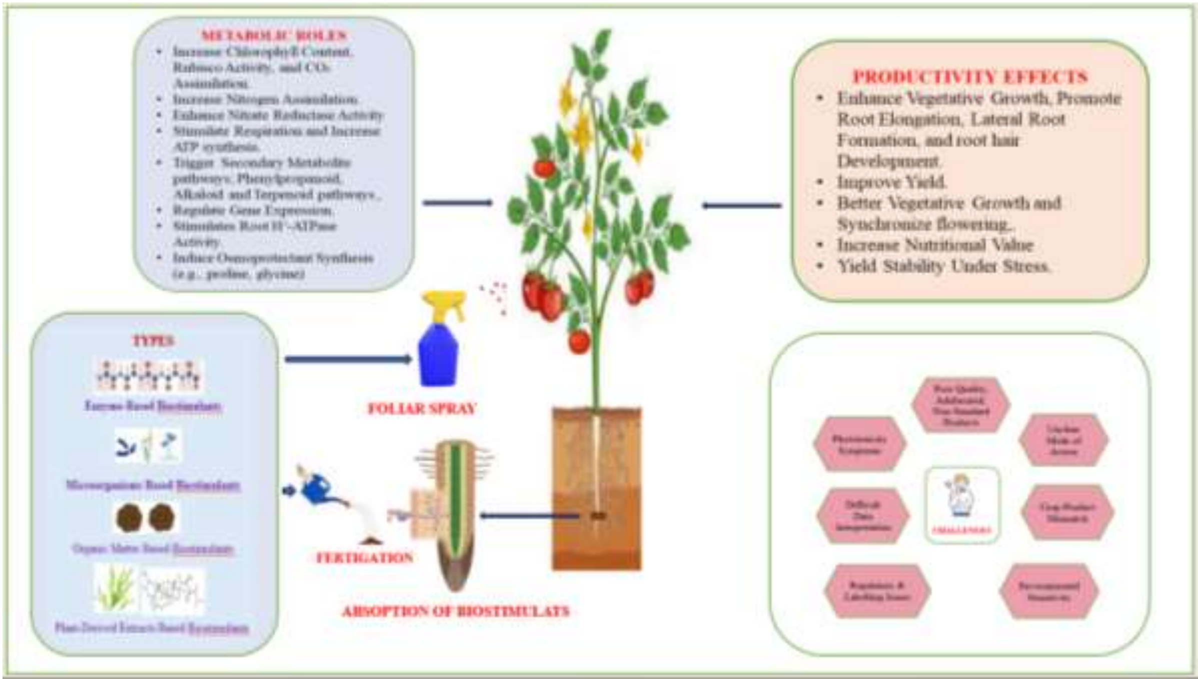


Fig. 8 Mechanism and productivity impact of biostimulants on plant growth

Global Economy and Agricultural Systems

Population Growth and Economic Development - Since 1950, the world population has expanded from 2.5 billion to over 8 billion, with projections indicating it will surpass 9 billion by 2050 (United Nations, 2022). This rapid growth, combined with rising incomes, especially in developing countries, is a major driver of increased food demand (OECD/FAO 2024; Seifollahi-Aghmiuni et al. 2022). Consequently, agricultural systems are under pressure to expand and intensify. Economic development has facilitated industrialization, urbanization, and the mechanization of agriculture, thereby improving productivity. However, this has also heightened reliance on resource-intensive practices, particularly synthetic fertilizers and pesticides. The combination of limited land and water availability with rising demand further reinforces reliance on intensive agricultural systems.

Agricultural Land Use and Associated Challenges - Approximately 37% of Earth's land surface is used for agriculture (FAO, 2020; OECD/FAO, 2024). While this figure underscores the scale of land already dedicated to food production, it also highlights the limited room for further expansion. The conversion of natural ecosystems such as forests and grasslands into farmland has had profound ecological consequences, including biodiversity loss, habitat fragmentation, and soil degradation. Efforts to reconcile food production with environmental protection have led to the adoption of practices like crop rotation, agroforestry, and sustainable land management. However, agricultural land remains under persistent threat from climate change, urban sprawl, and other anthropogenic pressures. These dynamics underscore the urgent need for more efficient, ecologically sound land-use strategies (Thwaites et al. 2025; Daszkiewicz 2022).

Fertilizer Use and Productivity in Global Agriculture - Synthetic fertilizers have been central to modern agricultural productivity. Their widespread use since the mid-20th century, particularly nitrogen (N), phosphorus (P), and potassium (K) fertilizers, has transformed crop yields by supplying essential nutrients that may be absent or deficient in soil (Yakhin et al. 2017). As of 2021, global fertilizer consumption exceeded 190 million metric tons, with Asia, especially China and India, accounting for the highest usage (FAO, 2023; OECD/FAO, 2024). While fertilizers are critical to achieving high yields, excessive or inefficient use contributes to environmental degradation. Surplus nutrients often leach into water bodies, causing eutrophication, algal blooms, and deterioration of water quality. Furthermore, nitrogen fertilizers are a major source of nitrous oxide, a greenhouse gas with a global warming potential approximately 300 times greater than carbon dioxide. Globally, nitrogen (N) fertilizer use has increased much faster than phosphorus (P) and potassium (K), as evidenced by studies by Lu and Tian and others. Human-induced inputs of N, P, and K now approximate the scale of natural biogeochemical fluxes, resulting in pronounced nutrient stoichiometric imbalances, particularly in N:P and N:K ratios. These disruptions in nutrient cycling and distribution reflect temporally and spatially uneven patterns of fertilizer consumption, with far-reaching implications for environmental integrity, food security, and the sustainability of agricultural systems (Dubey & Sharma 2023; Sible et al. 2025).

Environmental Consequences of Fertilizer Overuse - The environmental ramifications of synthetic fertilizer dependence are diverse and far-reaching. Soil health can be compromised when fertilizer is overused, as this alters microbial communities, reduces soil organic matter, and leads to acidification. These effects can erode the long-term sustainability and productivity of agricultural systems. Nutrient runoff remains a prominent threat to aquatic ecosystems. Fertilizer discharge into rivers and lakes accelerates eutrophication, significantly reducing water oxygen levels and leading to the formation of dead zones (Ansari et al. 2024; Meena et al. 2020; Bhardwaj et al. 2022). The Gulf of Mexico exemplifies this problem, where nutrient inflows from the Mississippi River have triggered large-scale algal blooms and a corresponding loss of marine biodiversity (Torres et al. 2017). In addition to water pollution, synthetic fertilizers contribute to greenhouse gas emissions, both during field application and in their energy-intensive production. The agricultural sector represents a substantial share of global emissions, with fertilizers playing a significant role in this footprint.

Plant biostimulants enhance nutrient use efficiency by improving the plant's ability to absorb, translocate, and assimilate essential nutrients. Compounds such as humic substances, protein hydrolysates, and microbial inoculants stimulate root growth and activate nutrient transporter systems, enabling plants to utilize available nutrients more effectively. As a result, crops often require lower quantities of synthetic fertilizers to achieve comparable productivity levels, contributing to more efficient nutrient management and reducing the environmental impacts associated with excessive fertilizer application.The use of biostimulants may also contribute to mitigating greenhouse gas emissions associated with conventional agricultural practices. By improving nutrient use efficiency and reducing reliance on synthetic fertilizers, biostimulants can help lower emissions of nitrous oxide (N_2O), a potent greenhouse gas linked to nitrogen fertilizer application. Additionally, improved soil health and microbial activity may enhance soil carbon sequestration, further supporting climate-smart agricultural strategies.

Biostimulants as a Sustainable Agricultural Input - In response to the escalating environmental costs of chemical fertilizers, biostimulants have emerged as a sustainable alternative. These substances, ranging from seaweed extracts and humic acids to amino acids and beneficial microorganisms, are designed to enhance plant growth, nutrient uptake, and resilience to abiotic stress, without functioning as direct nutrient sources. Biostimulants improve nutrient use efficiency by activating soil microbial activity, enhancing nutrient bioavailability, and promoting overall plant health. Studies demonstrate that biostimulants can reduce the dependency on synthetic fertilizers, mitigate their adverse environmental impacts, and support soil regeneration. Their adoption is particularly prominent in organic agriculture and integrated pest management systems, where minimizing chemical inputs is a core objective. Driven by consumer demand for environmentally responsible food systems and a global push toward sustainable agriculture, the biostimulant market is poised for rapid growth in the coming years (Rouphael& Colla 2020).

Balancing Productivity and Sustainability - The interplay among population dynamics, economic development, land use, fertilizer dependency, and environmental sustainability poses a complex global challenge. As the population grows and demand for agricultural commodities intensifies, the strain on arable land and finite natural resources will continue to mount. While fertilizers have been instrumental in meeting past and current food production needs, their negative environmental impacts underscore the need for alternative and complementary strategies. Biostimulants offer a viable path forward by enhancing productivity in more sustainable and ecologically sensitive ways. Future agricultural systems must adopt innovative, integrated approaches that balance the urgent need for increased productivity with long-term environmental stewardship. This will require interdisciplinary collaboration spanning agronomy, environmental science, economics, and policy-making, with the shared objective of fostering resilient, efficient, and sustainable global food systems (Baltazar et al. 2021)(Roche et al. 2024).

Role of Biostimulants in Sustainability Goals

Biostimulants and Sustainable Food Systems - Sustainable food systems are designed to ensure adequate food production for a growing global population while simultaneously reducing environmental degradation, conserving biodiversity, and maintaining long-term ecological integrity. Enzyme- and microorganism-based biostimulants contribute significantly to these objectives by enhancing soil health, improving nutrient use efficiency, and reducing dependence on synthetic agrochemical inputs.

Enhancing Soil Health and Fertility - Microbial communities are fundamental to maintaining soil health, primarily by promoting microbial biodiversity and facilitating nutrient cycling. Beneficial microorganisms, such as nitrogen-fixing bacteria and phosphate-solubilizing fungi, enhance the bioavailability of essential nutrients to plants, thereby decreasing the necessity for synthetic fertilizers. Enzyme-based biostimulants further contribute to this process by catalyzing the breakdown of organic matter, which releases key nutrients such as nitrogen, phosphorus, and potassium into the soil matrix. These improvements in nutrient availability not only increase soil fertility but also enhance soil structure, making it more resilient to erosion, compaction, and degradation (Selvan et al. 2023; Gomiero et al. 2011).

Reduction in Chemical Inputs - The use of enzyme and microorganism-based biostimulants can significantly reduce the agricultural sector's reliance on chemical fertilizers and pesticides. By promoting more efficient nutrient uptake and enhancing plant health, these biostimulants serve as natural alternatives to conventional agrochemicals. Certain beneficial microbes, including species of Bacillus and Trichoderma, produce bioactive secondary metabolites that confer protection against phytopathogens and insect pests. This biological form of pest and disease management reduces the need for synthetic pesticides, thereby contributing to environmentally sustainable agricultural practices and lowering the ecological footprint of food production systems (Saleem et al. 2024; Ansari et al. 2024).

Soil Microbiome Management - The targeted application of microorganism-based biostimulants can actively steer the soil microbiome toward more beneficial microbial communities. This ecological engineering of the rhizosphere supports improved plant growth and increased resilience to stress, while also fostering agroecosystems that align with sustainable farming principles. Through microbiome modulation, enzyme and microorganism-based biostimulants enable the development of low-input agricultural systems that maintain productivity without compromising long-term soil health and ecosystem function (Khoso et al. 2024; Ehinmitan et al. 2024).

The application of biostimulants positively influence soil microbial communities by promoting the growth and activity of beneficial microorganisms in the rhizosphere. Microbial biostimulants such as plant growth–promoting rhizobacteria (PGPR) and mycorrhizal fungi enhance nutrient cycling, organic matter decomposition, and the production of growth-promoting metabolites. Increased microbial diversity in the soil not only supports plant health but also contributes to improved ecosystem stability and resilience in agricultural soils.

Waste Bioremediation - Bioremediation, facilitated by specific microorganisms, has emerged as an effective approach for managing industrial waste. Microorganisms capable of degrading organic pollutants are now routinely applied to treat environmental contaminants such as oil spills and toxic industrial effluents. In parallel, enzyme-based biostimulants are being used to accelerate the decomposition of organic compounds in wastewater systems, reducing the reliance on hazardous chemical treatments. The implementation of these biological agents in waste management not only supports cleaner production processes but also aligns with broader goals of environmental compliance and sustainable industrial development.

Improved soil health indicators

Biostimulants have been shown to improve several key indicators of soil health, including soil organic matter content, enzymatic activity, and soil structure. By stimulating microbial processes and root exudation, biostimulants contribute to enhanced soil aggregation, improved water retention, and greater nutrient availability. These improvements in soil physical, chemical, and biological properties help maintain long-term soil fertility and support sustainable crop production.

Biodegradable Materials- Ongoing research and application of enzyme- and microorganism-based biostimulants have extended into the development of biodegradable materials. Certain microbial species synthesize biopolymers that serve as sustainable alternatives to conventional, petroleum-derived plastics. For example, enzymes such as polyhydroxyalkanoate (PHA) synthases catalyze the formation of bioplastics that are inherently biodegradable. These materials help reduce the accumulation of persistent plastic waste in the environment, offering a viable pathway toward more circular, less polluting material life cycles (Ranjithkumar 2025; Thwaites et al. 2025).

D. Global Market Overview

The global biostimulants market was valued at USD 2,982.9 million in 2022 and is forecast to reach USD 6,849.8 million by 2030, expanding at a Compound Annual Growth Rate (CAGR) of 11.19% during 2023–2030. Another estimate projects the market to touch USD 5.4 billion by 2027, growing at a CAGR of 10.2% between 2022 and 2027, underscoring the sector's robust expansion (Meena et al. 2025; Chakrabarty & Selvakumaran 2025; Jankuloska et al. 2025).

Number of companies - Isagro S.p.A., Biolchim S.p.A., Valagro S.p.A., Koppert Biological Systems, Biostadt India Limited, ChemChina group, Novozymes, Lallemand Plant Care, BASF SE, FMC Corporation, and many others are actively involved in the production of Biostimulants. Additional industry leaders such as Bayer CropScience, UPL Ltd., Syngenta AG, Gowan Group, ILSA S.p.A, Rallis India Limited, and Haifa Group are also prominently involved, reflecting the highly competitive and fragmented nature of the market (Khoulati et al. 2025; Rouphael& Colla 2020; Sible et al. 2021).

Growth in the sector is largely driven by the rising emphasis on sustainable agriculture, increased farmer awareness of the role of biostimulants in enhancing yield and quality, and escalating demand for organic produce. Equally significant is the need to reduce environmental impact through alternatives to chemical fertilizers. These drivers are complemented by technological innovations that yield new formulations with improved efficacy and crop-specific performance, as well as regulatory environments that increasingly support sustainable practices (Khoulati et al. 2025).

The adoption of precision agriculture highlights biostimulants' role in optimizing nutrient use and plant resilience. Consumer demand for sustainable and organic foods further boosts uptake, while digital technologies enable more precise applications and data-driven decision-making. Moreover, strategic collaborations between manufacturers and stakeholders are fostering region- and crop-specific solutions.

Segmentation of the global market provides further insight. By source, microbial biostimulants dominate, with the segment valued at USD 1,747.1 million in 2022, reflecting the growing appreciation of beneficial soil microbiota and their ability to support nutrient uptake and stress resistance. By form, liquid biostimulants are the fastest-growing, with a CAGR of approximately 11.95%, favored for their ease of application, rapid absorption, and compatibility with precision systems such as drip irrigation. Dry formulations remain relevant where shelf life and transport stability are prioritized. By active ingredient, the market spans vitamins and amino acids, seaweed extracts, microbial amendments, humic substances, protein hydrolysates, and others. Of these, the vitamins and amino acids segment held the highest valuation at USD 756.1 million in 2022, underscoring their importance in plant metabolic regulation, stress tolerance, and quality improvement (Critchley et al. 2021; Mandal et al. 2023).

Table 1 Global agricultural biologicals market size, forecasted growth, and key segmental and regional contributions, highlighting leading sources, formulations, applications, and their respective CAGR trends.

Metric	**Value**	**Year / Period**	**Notes**
Market Size	USD 2,982.9 million	2022	Global valuation
Forecasted Market Size	USD 6,849.8 million	2030	CAGR 11.19% (2023–2030)
Alternative Forecast	USD 5.4 billion	2027	CAGR 10.2% (2022–2027)

Microbial Segment Revenue	USD 1,747.1 million	2022	Largest revenue share by source
Vitamins & Amino Acids Segment	USD 756.1 million	2022	Largest by active ingredient category
Asia-Pacific Share of Global Market	38.67% (USD 1,153.5 million)	2022	Largest regional share
Europe Share of Global Market	~31%	2021	Largest regional market
Liquid Form CAGR	~11.95%	Forecast period	Fastest-growing form
Non-Microbial Segment CAGR	~10.5%	2022–2027	Large share segment
Seed Treatment CAGR	~8.9%	2022–2027	Fastest-growing application method

Regional analysis confirms that Europe dominates the global biostimulants market, accounting for roughly 31% in 2021, driven by the rapid adoption of organic farming and supportive EU agricultural policies. Asia-Pacific followed closely, with a 38.67% share (USD 1,153.5 million) in 2022, driven by population growth, food demand, government initiatives, and rising sustainability awareness. North America also contributes significantly, though Europe remains the single largest regional market (Critchley et al. 2021; Mandal et al. 2023; Khoulati et al. 2025; Naikoo et al. 2025).

Competitive strategies across the sector include partnerships, mergers and acquisitions, product innovations, and joint ventures. Companies continue to invest in research and development, capacity expansion, and supply chain optimization to strengthen their positioning. Report coverage, such as the "Biostimulants Market – Forecast (2022–2027)" by Industry ARC, reflects the breadth of segmentation: by form (dry, liquid), product type (microbial versus non-microbial), application method (foliar, soil, seed treatment), crop type (cereals, fruits, vegetables, plantation crops, turf and landscape), and detailed country-level geographies.

Several structural drivers underpin this market's expansion. Organic farmland is rising globally, as shown by FiBL statistics, while food demand is increasing amid limited arable land. FAO data highlight a 53% increase in primary crop production between 2000 and 2019, reaching 9.4 billion tonnes, while OECD projections suggest that future gains will rely heavily on yield improvements. Biostimulants are positioned as key enablers of this yield growth.

Challenges remain, particularly the commercialization of low-quality products by unorganized and local producers, which undermines farmer confidence and erodes the reputation of established brands. Nonetheless, the outlook remains strongly positive. Recent developments illustrate continued momentum, such as UPL AgroSolutions Canada's approval of OHM biostimulant (2021), UPL Australia's launch of GoActiv Technology (2021), and Acadian SeaplantsLtd's introduction of seaweed-based biostimulants (Acadian BioSwitch™) in India, targeting germination, yield, and weed suppression (Khoulati et al. 2025; Naikoo et al. 2025).

E. Indian Biostimulants Market

The Biostimulants sector is experiencing dynamic global growth, and the authors emphasized the Indian context, where a vast agricultural base, distinctive growth patterns, and emerging policy frameworks make the market significant (Naikoo et al. 2025). The Indian biostimulants market was valued at USD 79.2 million in 2022 and is projected to reach USD 189.7 million by 2030, expanding at a strong CAGR of 11.5% during 2023–2030. Despite its relatively small size, representing only about 3% of the global market in 2022, India is the fastest-growing market in the Asia-Pacific region, highlighting its rising importance in the global landscape. The market is segmented by active ingredients, with acid-based biostimulants dominating, accounting for 48.11% of revenue in 2022 (Indian Chamber of Commerce 2023)(IMARC Group 2025). This category's popularity stems from its ability to improve nutrient absorption, enhance soil fertility, and strengthen plant resilience under stress. At the same time, seaweed extracts represent the fastest-growing segment, benefiting from the rising adoption of organic farming practices and their compatibility with sustainable crop production systems. Other categories, including microbial-based and mixed active ingredient formulations, are steadily expanding as farmers embrace modern techniques that integrate biological inputs into conventional farming.

Several drivers underpin this robust growth. India’s growing population, rising consumer preference for organic and environmentally friendly food products, and increasing purchasing power are fueling demand for safe, high-quality produce. Farmers are also turning to biostimulants as effective alternatives to chemical fertilizers, reflecting greater awareness of their long-term benefits for crop yield and soil health. Simultaneously, modernization in agricultural techniques and the customization of products by Indian companies, such as Biostadt India Limited, to match specific crop and soil types, are further propelling adoption.

However, challenges remain in this fragmented market. A significant number of local and unorganized players compete with established companies, often by offering low-quality, low-cost products. This not only affects pricing dynamics but also threatens farmer confidence and brand credibility for premium products. Despite this, larger domestic players, including Rallis India Limited and UPL Ltd., alongside multinational corporations such as BASF SE, Isagro, Novozymes, Koppert, and others, continue to strengthen their presence through innovation, distribution expansion, and crop-specific product development.

Looking ahead, India’s biostimulants market is expected to consolidate its position as one of the fastest-growing globally, even as China emerges as the revenue leader within Asia-Pacific by 2030. With an expanding consumer base, government support for sustainable agriculture, and increasing private-sector innovation, India is set to play a pivotal role in shaping the region’s biostimulant landscape.

Table 2 The table outlines the national market size and growth outlook, segmental dominance, competitive landscape, and regional positioning, highlighting key drivers, players, and challenges shaping the market through 2030.

Metric	**Value**	**Year / Period**	**Notes**
Market Size	USD 79.2 million	2022	National valuation
Forecasted Market Size	USD 189.7 million	2030	CAGR 11.5% (2023–2030)
Share of Global Market	~3.0%	2022	Small but fastest-growing in APAC

Largest Active Ingredient Segment	Acid Based-48.11% revenue share	2022	Dominant segment
Fastest Growing Active Ingredient	Seaweed Extract	2023–2030	Organic farming adoption driver
Market Character	Fragmented	Ongoing	Mix of multinationals and local players
Key Domestic Players	Biostadt India, Rallis India, UPL Ltd.	Ongoing	Custom crop/soil solutions
Competitive Challenge	Low-quality products	Ongoing	Threat to brand trust
Regional Status	Fastest-growing in Asia-Pacific	Forecast to 2030	China to lead in total APAC revenue

F. Experimental Challenges in Evaluating Biostimulants

Experimental challenges in biostimulant research stem from their complex composition, variable effects, and the absence of standardized testing methodologies. Biostimulants, defined as substances or microorganisms that increase plant metabolic processes without functioning as a direct source of nutrients or pesticides, are being widely applied in sustainable agriculture, stress management, and nutrient efficiency enhancement (Baltazar et al. 2021)(Yakhin et al. 2017)(Delaeter et al. 2024). However, their heterogeneous formulations, especially those derived from natural sources such as seaweed extracts, humic substances, and protein hydrolysates, complicate their characterization (Bhupenchandra et al. 2020). Their composition varies significantly depending on the source material, extraction and processing techniques, resulting in significant variability between batches that makes reproducibility and standardization difficult. Furthermore, these products typically possess complex biological activity, as they contain multiple biologically active molecules or a consortium of microbial species. This complexity makes it difficult to attribute observed effects to a single component, and potential synergistic or antagonistic interactions among constituents further complicate the understanding of their specific modes of action. A major experimental challenge in biostimulant research is the lack of standardized protocols, which makes it difficult to maintain consistent results and compare across studies. Unlike pesticides or fertilizers that follow well-defined regulatory testing frameworks, biostimulants lack globally standardized experimental guidelines for efficacy evaluation (Khoulati et al. 2025)(Sun et al. 2024). Experimental design faces reproducibility issues due to environmental variability and challenges in scale-up from controlled to field conditions. Elucidating the mode of action of biostimulants remains one of the most complex experimental challenges in this field. Biostimulants are known to induce systemic or hormone-like responses in plants, which are difficult to trace using conventional physiological methods. To characterize these responses, advanced multi-omics approaches, such as transcriptomics, metabolomics, and proteomics, are required to elucidate the complex molecular and biochemical pathways involved. However, these techniques are resource-intensive and costly. Furthermore, the lack of universal biomolecular markers to confirm biostimulant activity makes it difficult to standardize assessments and validate its mechanism. The combination of biological complexity and limited methods makes it difficult to clearly understand how biostimulants work. Regulatory and claim-validation issues pose significant challenges to the proper evaluation and commercialization of biostimulants. Regulations like EU Regulation 2019/1009 require strong scientific proof for product claims, but there are no globally accepted testing methods, and overlaps with fertilizers or biopesticides make classification unclear. Data interpretation and meta-analysis in biostimulant research are limited by several significant challenges. One major issue is the heterogeneity of published data, as studies often involve different crop species, product formulations, application rates, experimental designs, and environmental conditions. This variability makes it difficult to integrate results or to conduct meaningful meta-analyses that yield generalized conclusions about efficacy. These challenges highlight the need for strong experimental design, standardized methods, advanced analytical tools, and close coordination between regulators and scientists to ensure reliable and meaningful evaluation of biostimulant products.

VISION AND FUTURE PERSPECTIVES

Over the past century, the use of synthetic fertilizers and pesticides has boosted food production but has also caused nutrient loss, soil degradation, water pollution, loss of beneficial microbes, greenhouse gas emissions, and higher costs for farmers. To find sustainable options, biofertilizers using helpful microbes to improve nutrient cycling were developed, but their effectiveness often varied in different farming conditions. This limitation paved the way for biostimulants, a broader category of products that extend beyond nutrient supply. Biostimulants encompass microbial and non-microbial agents that enhance plant growth, nutrient use efficiency, and resilience to abiotic stresses such as drought, salinity, and temperature extremes, while also improving crop quality traits. Their lack of toxicity, minimal ecological persistence, and multifaceted mechanisms of action position them as key enablers in the transition toward sustainable intensification. Looking ahead, biostimulants are poised to play a central role in future agricultural systems. However, several research gaps remain. First, their mechanisms of action are often poorly understood, with many effects documented empirically but lacking molecular or physiological validation. Second, their context dependency across soils, climates, crops, and even cultivars requires systematic multi-location, multi-year field trials to ensure reproducibility. Third, integration with precision agriculture and digital farming tools could unlock optimized application strategies, but remains underdeveloped. Fourth, regulatory frameworks are fragmented and lack harmonization, impeding global adoption and standardization. Finally, most assessments of biostimulant efficacy focus on yield; future work must incorporate economic analyses, input savings, soil health indices, and ecosystem service valuation to fully capture their benefits. To overcome these challenges, future research should adopt an interdisciplinary approach combining molecular biology, plant physiology, soil science, and agronomy with socio-economic and policy perspectives. At the policy level, harmonized regulations and quality standards are essential to filter out ineffective products and strengthen farmer confidence. By addressing these gaps, biostimulants can evolve from promising innovations into foundation technologies for achieving sustainable, resilient, and climate-smart agriculture.

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RK: Conceptualization, formal analysis, investigation, data curation, visualization, and writing-original draft; NK: Critical review and revision, Methodology, Writing-review & editing, AS: Conceptualization, Formal analysis; RKS: Methodology, Data curation, Visualization, Writing-review & editing.

CONSENT FOR PARTICIPATION

Not applicable.

ETHICAL CONSENT

Not applicable.

CONSENT FOR PUBLICATION

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AVAILABILITY OF DATA AND MATERIALS

The data and supporting information are available within the article.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest, financial or otherwise.

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