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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 substances, either natural or synthetic, that enhance plant growth without functioning as fertilizers or pesticides. According to the European Biostimulants Industry Council and EU regulations, biostimulants improve the efficiency of nutrient use, help plants withstand challenging conditions, and increase crop yields by activating specific plant functions. Unlike biofertilizers, which supply nutrients through living microbes, biostimulants influence plant development and interactions with beneficial microbes. The main types include enzyme formulations, beneficial microbes such as fungi and bacteria that promote growth, natural soil-derived acids, digested proteins, amino acids, and extracts from plants and seaweed. These products enhance root development, nutrient absorption, water regulation, and stress resistance. As climate change, soil degradation, and the demand for sustainable agriculture intensify, biostimulants present a promising alternative to chemical fertilizers by strengthening crop resilience and supporting environmental health. The global biostimulants market was approximately USD 3.0 billion in 2022 and is projected to reach USD 5.4–6.85 billion by 2027–2030, driven largely by microbial and liquid formulations. Europe leads in biostimulant adoption, but rapid growth is also occurring in Asia–Pacific, particularly in India, which represents a significant and expanding market. Despite ongoing challenges related to regulations, testing, and quality assurance, biostimulants are emerging as vital tools for sustainable farming and food security.

1. INTRODUCTION

The increasingly interconnected global economy continues to heighten the importance of agricultural systems in supporting human populations. As the world's population surpasses 8 billion and economic growth accelerates, the demand for vital commodities such as food, fiber, and biofuels has surged (OECD/FAO 2024, Anderson 2023). However, the limited availability of arable land increasingly restricts expansion. To meet these demands, agriculture has intensified, notably through widespread use of synthetic fertilizers, which raises significant environmental concerns. Global climatic changes and local adverse conditions are increasingly limiting agricultural productivity and crop quality. Environmental stressors, including elevated atmospheric CO_2, global warming, soil salinization, desertification, and nutrient imbalances caused by toxicity or deficiencies, adversely impact plant growth, development, yield, and quality.

In severe cases, these factors have caused species decline and localized extinctions. Empirical studies show that abiotic stressors have reduced yields of

major crops by over 50% (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 example, rice (Oryza sativa) yields dropped by 15% with every 1 °C increase in temperature from 1979 to 2003 (Impa et al. 2021). Furthermore, climate variability increases plant vulnerability to pathogens, worsening growing conditions (Kumar et al. 2023, Jing et al. 2024, Wang et al. 2018). At the same time, urbanization and climate-driven land degradation reduce arable land, posing additional risks to global food security, especially as food production must double by 2050 to meet the growing population's needs (Seifollahi-Aghmiuni et al. 2022, Bununu et al. 2023, Ranjithkumar 2025).

In response to mounting pressures, the Green Revolution and subsequent agricultural intensification have relied heavily on synthetic fertilizers and pesticides. However, nutrient uptake remains inefficient, with only 10–20% of nutrients absorbed by plants and as little as 0.1% of pesticides reaching their intended targets. These chemicals often 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). Consequently, reducing chemical inputs is vital for sustainable agriculture. Biostimulants (BSs) present promising alternatives due to their bioactivity, non-toxicity to non-target organisms, and environmental persistence. Incorporating biostimulants into modern crop management reflects a growing emphasis on environmentally sustainable, efficient practices. BSs contribute to nutrient cycling, stress tolerance, and microbial interactions, making them valuable tools for resilient and productive farming (Rouphael & Colla 2020a, Khoulati et al. 2025a).

Although research on agricultural biostimulants is still emerging, their potential is significant. Continued studies on their mechanisms can lead to optimized applications (Baltazar et al. 2021, Roche et al. 2024, Bhupenchandra et al. 2022, Johnson et al. 2024). Recent plant science research increasingly supports the role of biostimulants in enhancing crop productivity and resilience. This review explores the various types and functions of biostimulants, along with the challenges, market prospects, and sustainability issues involved**.**

2. MATERIALS AND METHODS

2.1. Data Source and Search Strategy

In this study, we utilized the Scopus database to gather articles related to biostimulants and sustainable agriculture, with data collection completed on January 12, 2026. The analysis of this data is presented in Fig. 1. Our search included keywords such as "biostimulant," "biofertilizer," "plant growth promoter," and "microbial inoculant," along with phrases like "sustainable agriculture," "sustainable farming," "agricultural sustainability," "environmentally friendly agriculture," and "environmentally friendly farming." Only articles published between 2015 and 2025 were considered. We extracted information on the articles themselves, their authors, countries, institutions, journals, keywords, and citation counts.

2.2. Inclusion and Exclusion Criteria

To maintain consistency and focus, we included only

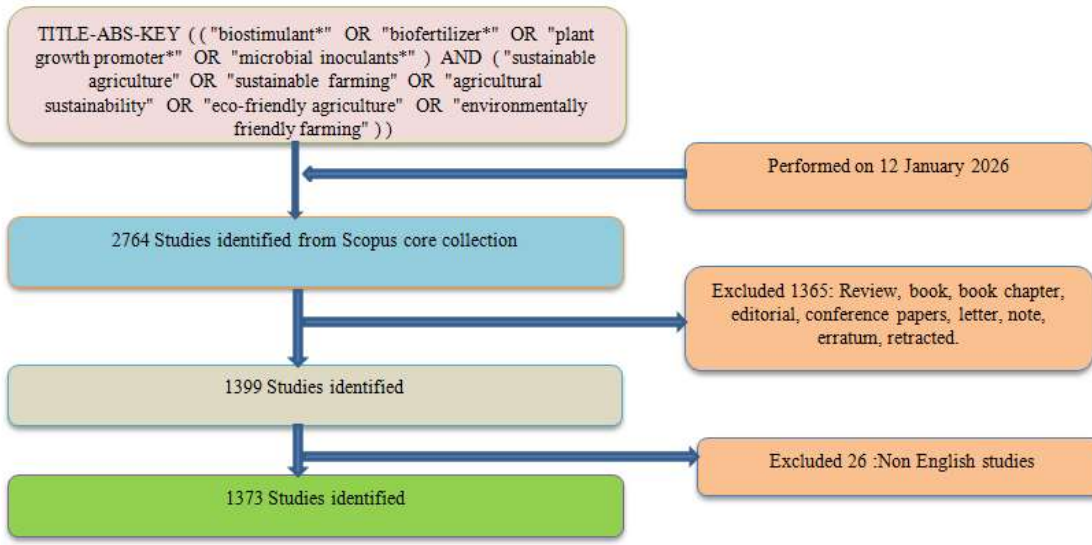


Fig. 1: Strategy for data retrieval and collection.

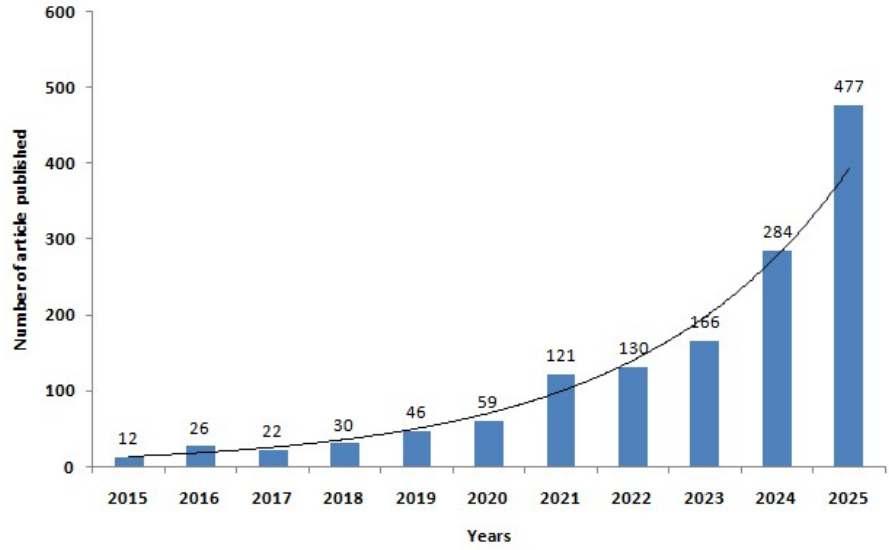


Fig. 2: Publication trend in the number of articles related to biostimulants for sustainable agriculture in the past decade.

documents labeled as 'articles.' This approach prioritized original research, which typically presents clear methods and primary data. We manually reviewed the most cited articles on the topic to ensure no significant works were overlooked. We excluded reviews, book chapters, short surveys, notes, books, and retracted papers, as they often lack sufficient data or comprehensive analysis. Nonetheless, we verified that excluding these types did not omit any major contributions relevant to our study.

2.3. Research Trends on Biostimulants for Sustainable Agriculture

We evaluated annual research growth by analyzing the publication years of relevant articles. Fig. 2 illustrates the distribution of publications from 2015 to 2025. The findings reveal a growing interest among researchers in biostimulants for sustainable agriculture. A search of electronic databases identified 2,764 records, of which 1,391 were excluded based on the study's criteria, leaving 1,373 articles for further review.

Several reasons drive the upward trend in academic research. This has facilitated the development of practical methods for using biostimulants in sustainable farming. This increase in research activity has resulted in notable achievements, advancing sustainable solutions in agriculture.

2.4. Subject Area Distribution

A total of 1,373 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. 3).

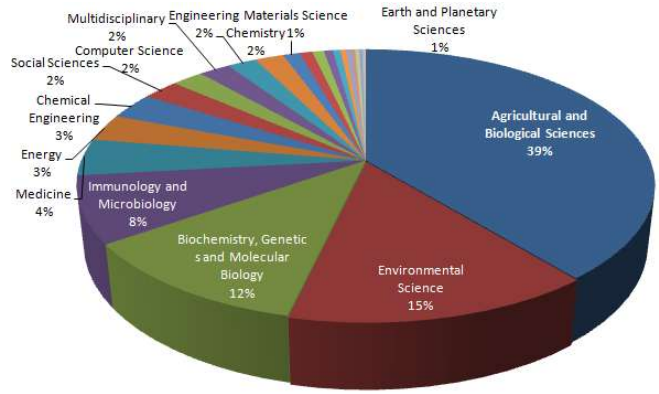


Fig. 3: Subject-wise distribution of articles related to biostimulants for sustainable agriculture in the past decade.

2.5. Most Productive Countries

As demonstrated in Fig. 4, a total of 1,373 publications were produced by researchers from 110 countries and regions, with the top 10 nations contributing to biostimulants research for sustainable agriculture. India led with 272 publications, followed by Italy with 155, China with 144, the USA with 86, and Brazil with 79. Fig. 4 also analyzes co-authored papers involving scholars from different countries on this topic. The data reveal that China has a notably higher number of international collaborations in this field. Publications from China, the USA, and Italy account for over 40% of all articles published (Fig. 4).

2.6. Biostimulants: A Solution to Mitigate Agricultural Problems

In recent years, modern agricultural systems have faced the complex challenge of simultaneously ensuring global food security while promoting sustainable farming practices. On the one hand, there is a pressing need to implement highly efficient agricultural methods that increase crop productivity to satisfy the demands of a rapidly growing population. On the other hand, these methods must adhere to environmentally friendly principles that safeguard environmental health and human well-being. To intensify production, the widespread use of mineral fertilizers and agrochemicals has become standard. However, the overuse and long-term application of these chemicals have caused significant adverse effects, including soil degradation, declining crop yields over time, and pollution of air, water, and land ecosystems (Selvan et al. 2023, Gomiero et al. 2011). These issues raise serious concerns about environmental sustainability and public health.

In response, the adoption of biobased products, such as biostimulants and biofertilizers, has gained attention as a promising approach to enhance crop yields, improve nutrient absorption, mitigate abiotic stress, and align agricultural practices with sustainability goals. Derived from natural sources, these bio-products differ fundamentally from conventional soil conditioners in origin, composition, and biological activity. Both biostimulants and biofertilizers are non-toxic to plants, soil, and consumers, making them safer alternatives to chemical inputs. While biofertilizers supply nutrients through active microbial processes like nitrogen fixation and phosphate solubilization, biostimulants primarily influence plant physiology and rhizosphere interactions without serving as direct nutrient sources (Calvo et al. 2014, Rouphael & Colla 2020a, 2020b, Bhupenchandra et al. 2020).

Biostimulants are a diverse group of natural or synthetic inputs that enhance plant performance by activating innate biological processes rather than directly supplying nutrients (Fig. 5). They aid in improving nutrient uptake and utilization efficiency, increase tolerance to abiotic stresses such as drought, salinity, and heat, and can enhance crop quality while promoting more sustainable production methods (Bhupenchandra et al. 2020, Du Jardin 2015). According to the European Biostimulants Industry Council (EBIC 2016), biostimulants are substances and/or microorganisms applied to plants or the rhizosphere that stimulate natural processes, leading to improved nutrient absorption, nutrient use efficiency, stress tolerance, and crop quality. From a regulatory perspective, European Regulation (EU) 2019/1009 defines plant biostimulants as products that

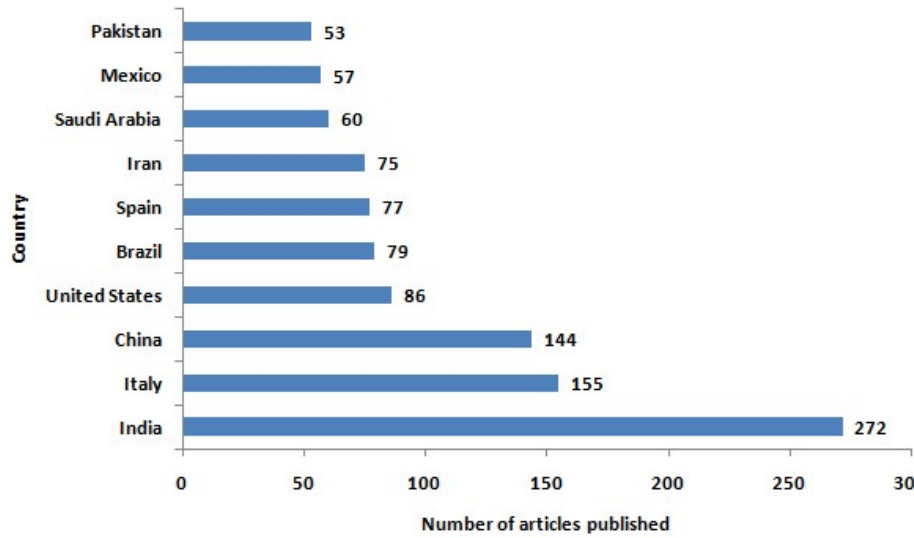


Fig. 4: Top 10 countries publishing the highest number of articles.

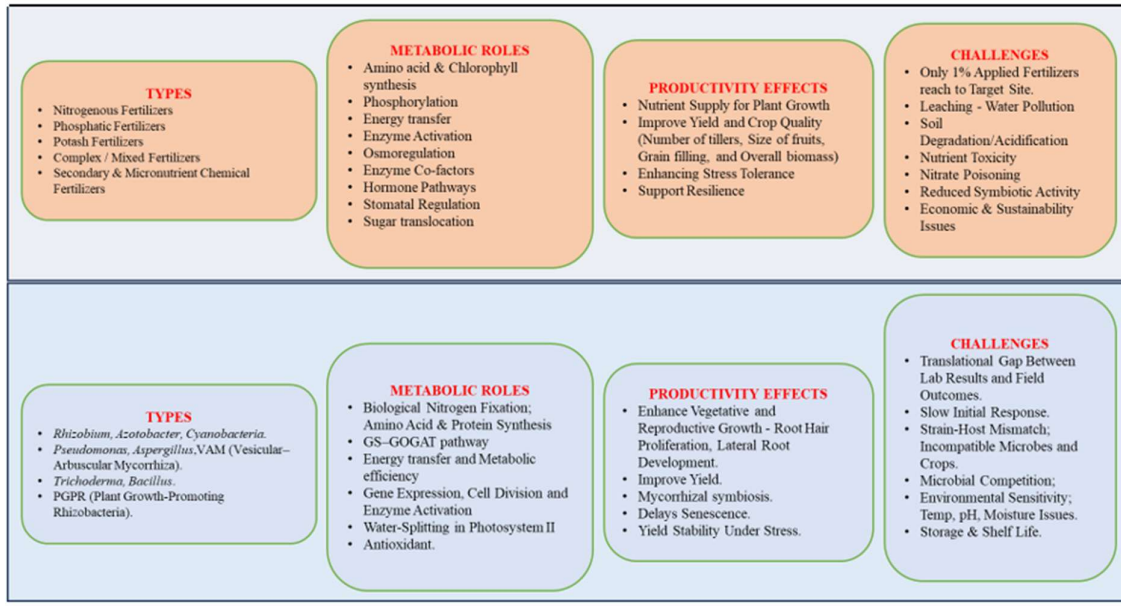


Fig. 5: Types, metabolic roles, productivity effects, and challenges of chemical and biological fertilizers.

promote nutritional processes independently of their nutrient content, with four main aims: (i) boosting nutrient use efficiency, (ii) enhancing tolerance to abiotic stresses, (iii) improving crop quality traits, and (iv) increasing nutrient availability in soil or the rhizosphere (Yakhin et al. 2017, Papnai et al. 2022, Dubey & Sharma 2023).

The regulation encompasses a wide array of qualifying substances and organisms, including humic substances, protein hydrolysates and amino acid-based products, extracts from macro- and microalgae and plants, silicon-based products, and beneficial microorganisms. Notably, microbial categories include arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR), especially species within the genera Azotobacter, Azospirillum, and Rhizobium (Sible et al. 2025, Yakhin et al. 2017, Delaeter et al. 2024, Chabili et al. 2024).

The effectiveness of plant biostimulants varies significantly depending on factors such as crop species, soil properties, and climate conditions. Different plant species and cultivars exhibit diverse responses to biostimulant treatments due to differences in physiological traits, nutrient needs, and metabolic processes. Likewise, soil characteristics like pH, organic matter levels, nutrient availability, and microbial activity can affect how well biostimulant formulations work. Environmental variables, including temperature, rainfall, and water accessibility, are also critical in shaping plant responses. As a result, the positive effects seen in one cropping system or agroecological zone may not be observed under different environmental conditions.

In addition to environmental variability, the literature presents inconsistent findings regarding yield improvements and stress tolerance associated with biostimulant use. Although numerous studies show enhanced crop productivity and increased tolerance to stresses such as drought, salinity, and nutrient deficiency, some investigations report only limited or variable benefits. These differences may stem from variations in experimental conditions, biostimulant formulations, application techniques, and crop management practices. This variability underscores the need for more systematic, well-controlled research to better understand the conditions under which biostimulants reliably deliver agronomic advantages and to develop optimized application strategies tailored to diverse cropping systems.

2.7. Types of Biostimulants

Biostimulants represent a diverse range of biologically active compounds and organisms that promote plant growth, improve nutrient uptake, and enhance stress tolerance. These encompass both enzyme-based and microorganism-based types, each operating through unique mechanisms to support plant development and soil vitality.

2.7.1. Microbial Biostimulants

Mycorrhizal fungi, particularly those from the Glomus genus, form vital mutualistic relationships with plant roots. These fungi effectively expand the root system, significantly enhancing the absorption of essential nutrients such as phosphorus, nitrogen, and various micronutrients. They also aid in water uptake, increase resistance to soil-borne pathogens,

and improve plant resilience under stressful conditions like drought or nutrient-deficient 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 vigor. In addition to their nutritional roles, many beneficial microbes induce systemic resistance in plants, providing 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 & Rillig 2015, Singh et al. 2024). The 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 vigor (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, environmentally friendly alternative to chemical fertilizers and pesticides, supporting the transition toward more resilient, environmentally responsible agricultural systems.

2.7.2. Seaweed Extracts

Seaweed extracts are abundant in biologically active compounds such as vitamins, minerals, amino acids, and natural plant hormones, all of which support plant growth, development, and overall health. Key among these are auxins and cytokinins, which significantly enhance seed germination, stimulate root development, and boost vigor across various crop species. The combined action of natural compounds in marine plant extracts promotes balanced vegetative and reproductive growth and increases the resilience of plants to abiotic and biotic stresses under both controlled and field conditions. Under challenging conditions like water stress, biostimulant treatments with plant extracts, combined with amino acids or yeast extracts, have increased maize yields by 8.5–20%, demonstrating their role in stress mitigation (Jaikumar et al. 2024).

Additionally, multi-component biostimulant formulations incorporating plant extracts have raised tomato productivity by 39–57%, depending on irrigation levels (Patanè et al. 2025). Recent advances in formulation technology have enabled the creation of innovative biostimulants that combine seaweed extracts with other bioactive ingredients to enhance effectiveness and expand applications in modern agriculture (Patanè et al. 2025, Kumar et al. 2025). These multifunctional formulations not only improve crop performance but

also support sustainable farming practices by providing environmentally friendly alternatives to chemical fertilizers.

2.7.3. Humic and Fulvic Substances

Humic and fulvic acids play a crucial role in plant physiology and plant-soil interactions. They influence root system architecture by stimulating lateral root initiation and root hair development, thereby enhancing the plant's absorptive surface area.

Additionally, these acids impact membrane transport processes, including ion channel activity and proton pump regulation, which improves the uptake and translocation of essential nutrients (Canellas et al. 2015). By increasing cation exchange capacity and chelating micronutrients, humic and fulvic acids significantly boost nutrient solubility and bioavailability, enabling more efficient nutrient absorption across various soil conditions. Biostimulants derived from humic and fulvic acids enhance the fertilization efficiency of key nutrients such as potassium, nitrogen, and phosphorus. Moreover, they facilitate the mobilization of minerals like iron, zinc, copper, and manganese in soils, increasing their availability to plants and aiding in water and nutrient retention (Akinci 2009).

Numerous studies have demonstrated the benefits of incorporating humic and fulvic acids to maintain soil quality and improve crop yields. Haider et al. (2017) reported that applying humic acid to soil at rates of 10, 20, and 30 kg ha^{-1} increased pod weight, resulting in higher yields. An experiment on tomatoes showed that total yield increased by 10–15% when a nutrient mixture and biostimulants were applied through foliar and soil treatments (Mallick et al. 2024). Pillajo et al. (2024) highlighted that humic compounds could serve as a viable alternative to reduce fertilization rates in Solanum lycopersicum cultivation while maintaining healthy growth and nutrition. They suggested that humic acid might be an effective substitute for lowering fertilizer inputs without compromising yield or plant health (Pillajo et al. 2024). AL-Taey et al. (2019) found that the highest head weight and yield were achieved with the combined application of biofertilizer (20 g L^{-1}) and humic acid (10 mL L^{-1}), compared to using biofertilizer alone in Brassica oleracea (Al-Taey et al. 2019). Similarly, Dawood et al. (2019) observed that applying varying levels of humic acid (0% to 5%) to Vicia faba resulted in higher seed yields compared to the control (Dawood et al. 2019).

2.7.4. Protein Hydrolysates and Amino Acid-Based Biostimulants

Protein hydrolysates and amino acid-based biostimulants influence plant growth and stress resilience by regulating nitrogen metabolism and enhancing the activity of vital enzymes such as nitrate reductase and glutamine synthetase, thereby bolstering nitrogen assimilation and protein synthesis. Amino acids also serve as osmoprotectants, aiding plants in maintaining cellular homeostasis under abiotic stresses like drought, salinity, and temperature extremes.

Additionally, many amino acids function as signaling molecules that activate antioxidant defense mechanisms, which improve the scavenging of reactive oxygen species (ROS) and safeguard cellular structures from oxidative damage (Colla et al. 2017, Calvo et al. 2014). Derived from protein hydrolysis, amino acids and peptides are crucial for plant growth, development, and stress management through various physiological and biochemical pathways. These compounds also enhance nutrient uptake, boost photosynthetic efficiency, and increase plant resilience to environmental stresses, acting as osmoprotectants and signaling entities.

Moreover, amino acids and peptide-based biostimulants are deeply integrated into nitrogen and sulfur metabolic pathways, serving as essential precursors for enzyme, chlorophyll, and other metabolite biosynthesis that regulate plant metabolism (Heidarzadeh 2025, Khoulati et al. 2025b). In vitro studies by Tamburino et al. (2023) demonstrated that enzyme molecules such as chitinase, xylanase, and β-glucosidase, used as biostimulants in Lactuca sativa, significantly increase cell biomass, 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.

2.7.5. Plant-Derived Compounds and Other Emerging Biostimulants

Seaweed and higher-plant extracts are significant categories of biostimulants because they contain complex mixtures of bioactive compounds such as polysaccharides, betaines, and phenolic compounds. These molecules influence plant signaling pathways, improve nutrient uptake efficiency, and bolster plant resilience against abiotic and biotic stresses. Compost tea contains a diverse array of microbial species, which can be classified as microbial inoculants, even though it also includes proteins, amino acids, and humic substances (Villa e Vila et al. 2024, Ali et al. 2021, Han et al. 2024).

2.7.6. Enzyme-Based Biostimulants

Phosphatase enzymes, especially phytases, are essential in releasing phosphorus from organic compounds in the soil. As phosphorus is a vital macronutrient that often limits crop growth, these enzymes enhance its bioavailability by converting organic phosphorus into inorganic phosphate forms that plants can easily absorb. Fungi like Aspergillus

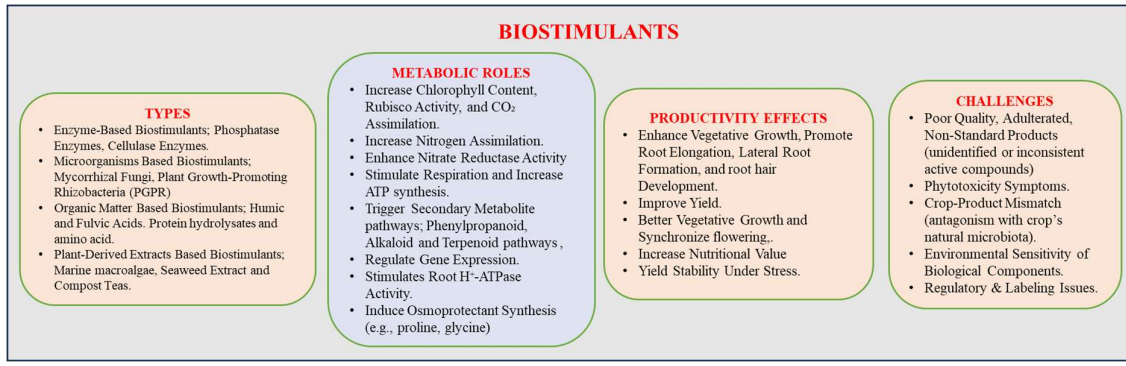


Fig. 6: Major types, metabolic roles, productivity effects, and challenges of biostimulants.

and bacteria such as Bacillus are well-known producers of phytase and are frequently included in enzyme-based biostimulant products.

Cellulase enzymes facilitate the breakdown of cellulose found in plant residues and organic matter. This enzymatic activity promotes nutrient cycling, improves soil structure, and stimulates microbial activity within the rhizosphere, thereby enhancing nutrient availability to plants. Fungi from the Trichoderma genus and bacteria such as Bacillus subtilis are capable of producing cellulase enzymes and are often incorporated into biostimulant formulations for these purposes (Rouphael & Colla 2020a, 2020b, Zamljen et al. 2023, Tamburino et al. 2023). Amino acids and peptides, derived from protein hydrolysis, are crucial for plant growth, development, and stress tolerance. These compounds increase nutrient uptake, boost photosynthetic efficiency, and improve plant resilience against environmental stresses by acting as osmoprotectants and signaling molecules.

Biostimulants based on amino acids and peptides support nitrogen and sulfur metabolism by serving as precursors for enzymes, chlorophyll, and other key metabolites, thereby regulating plant metabolic processes (Phooi et al. 2022). Tamburino et al. (2023) evaluated several enzyme molecules, including chitinase, xylanase, and β-glucosidase, as biostimulants in Lactuca sativa, reporting biomass increases of up to 50% and 40% for xylanase at concentrations of 0.1 and 0.01 µM, respectively, and increases of 60% and 30% for β-glucosidase at the same concentrations in vitro.

Patanè et al. (2025) observed productivity increases of 57% under no irrigation stress and 39% under full irrigation in *Solanum lycopersicum* when treated with enzyme-based biostimulants compared to controls (Bashir et al. 2025). In agriculture, these biostimulants are typically applied via foliar sprays or soil amendments, leading to enhanced plant growth, yield, and quality across various crops. Recent advances focus on biotechnological innovations, such as enzymatic hydrolysis, fermentation technologies, and nano-formulations, to optimize production, formulation, and delivery for maximum effectiveness. Notably, amino acid and peptide-based biostimulants support sustainable agriculture by reducing reliance on chemical fertilizers and pesticides, thereby aligning with environmentally friendly farming practices (Ranasingha et al. 2024, Khoulati et al. 2025a, Sun et al. 2024).

2.8. Mechanism of Action of Biostimulants

Plant biostimulants enhance plant growth and resilience to stress by influencing their metabolism, nutrient absorption, and microbial interactions. They primarily operate by modulating hormone signals, particularly those involving auxins, cytokinins, and gibberellins. Many biostimulants, including seaweed extracts and microbial formulations, either contain hormone-like compounds or stimulate plants to produce more hormones. This results in increased cell division, growth, and overall development. Auxin-like effects promote root branching and elongation, while cytokinins encourage shoot growth and delay leaf senescence. Gibberellins facilitate stem elongation and seed germination, strengthening the plant and boosting productivity. Additionally, biostimulants improve nutrient uptake and transport by enhancing root transporter activity and activating genes responsible for nutrient movement. Consequently, plants absorb higher amounts of essential nutrients such as nitrogen, phosphorus, potassium, and iron. Some biostimulants also activate enzymes that help plants utilize these nutrients more efficiently, reducing their reliance on chemical fertilizers.

Biostimulants influence root development and soil interactions, which are crucial for plant health and nutrient movement within the soil. The application of humic substances, protein hydrolysates, and microbial biostimulants promotes root branching, enhances root hair growth, and increases overall root biomass. These modifications expand the root surface area, improving water and nutrient

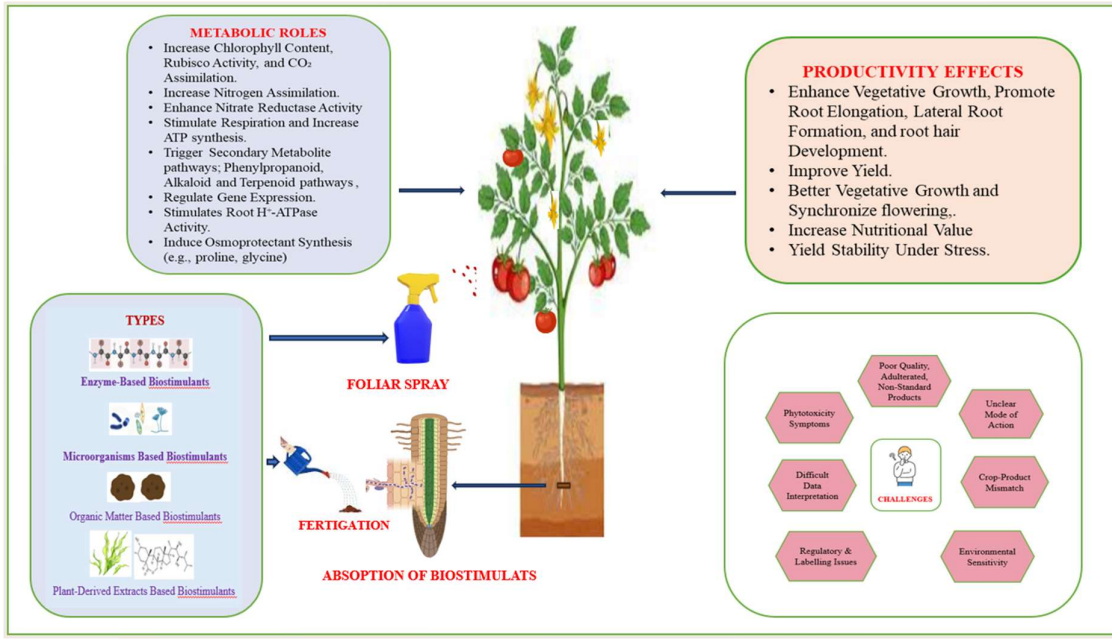


Fig. 7: Mechanism and productivity impact of biostimulants on plant growth.

absorption, and also bolster the plant's resilience to challenging conditions such as drought and salinity.

Another key function of biostimulants is enhancing the interaction between plants and beneficial microbes. Microorganisms such as plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi increase nutrient availability for plants. They also secrete substances that promote plant growth and improve stress resistance. These microbes inhabit the regions around plant roots or within plant tissues, sending signals that regulate plant defenses and metabolism. Through these mechanisms, biostimulants support improved plant growth and stress tolerance and contribute to more sustainable agricultural practices (Fig. 7).

2.9. Global Economy and Agricultural Systems

Population Growth and Economic Development: Since 1950, the global population has grown from 2.5 billion to over 8 billion, with projections suggesting it will exceed 9 billion by 2050 (United Nations 2022). This rapid increase, coupled with rising incomes, particularly in developing countries, has driven a significant rise in food demand (OECD/FAO 2024, Seifollahi-Aghmiuni et al. 2022). As a result, agricultural systems are under increasing pressure to expand and intensify. Economic development has spurred industrialization, urbanization, and mechanization in agriculture, leading to higher productivity. Nonetheless, this progress has also increased dependence on resource-intensive practices, such as synthetic fertilizers and pesticides. The limited availability of land and water, combined with growing demand, further reinforces the need for intensive agricultural approaches**.**

Agricultural Land Use and Associated Challenges: Approximately 37% of Earth's land surface is committed to agriculture (FAO 2020, OECD/FAO 2024). While this statistic highlights the extensive extent of land dedicated to food production, it also emphasizes the limited scope for future expansion. Transforming natural ecosystems such as forests and grasslands into farmland has caused significant ecological impacts, including loss of biodiversity, habitat fragmentation, and soil deterioration. Initiatives to balance food production with environmental preservation have promoted practices like crop rotation, agroforestry, and sustainable land management. Nevertheless, agricultural land continues to face ongoing threats from climate change, urban expansion, and other human activities. These challenges reinforce the urgent need for more efficient and ecologically sustainable land-use strategies (Thwaites et al. 2025, Daszkiewicz 2022).

Fertilizer Use and Productivity in Global Agriculture: Synthetic fertilizers have played a pivotal role in advancing modern agriculture. Since the mid-20th century, their widespread application, particularly nitrogen (N), phosphorus (P), and potassium (K) fertilizers, has significantly boosted crop yields by providing essential nutrients that may be deficient or absent in soil (Yakhin et al. 2017). By 2021, global fertilizer consumption surpassed 190 million metric tons, with Asia, especially China and India, leading the demand (FAO 2023, OECD/FAO 2024). Although fertilizers

are vital for achieving high productivity, their excessive or inefficient use can harm the environment. Excess nutrients often leach into water bodies, leading to eutrophication, algal blooms, and declining water quality. Additionally, nitrogen fertilizers are a primary source of nitrous oxide, a potent greenhouse gas with a global warming potential roughly 300 times that of carbon dioxide. The use of nitrogen (N) fertilizer has grown at a rate far exceeding that of phosphorus (P) and potassium (K), as demonstrated by research from Lu and Tian and others. Human inputs of N, P, and K now rival natural biogeochemical fluxes, causing notable nutrient imbalances, especially in N:P and N:K ratios. These disruptions in nutrient cycling and distribution exhibit spatial and temporal variability in fertilizer use, with significant consequences for environmental health, food security, and sustainable agriculture (Dubey & Sharma 2023, Sible et al. 2025).

Environmental Consequences of Fertilizer Overuse: The environmental impacts of reliance on synthetic fertilizers are extensive and multifaceted. Overapplication of fertilizers can harm soil health by disrupting microbial communities, decreasing soil organic matter, and causing acidification, all of which threaten the long-term sustainability and productivity of agricultural systems. Nutrient runoff also poses a significant risk to aquatic environments; discharges into rivers and lakes accelerate eutrophication, depleting oxygen levels and creating dead zones, as exemplified by the Gulf of Mexico, where nutrient inflows from the Mississippi River have caused extensive algal blooms and marine biodiversity loss (Ansari et al. 2024, Meena et al. 2020, Bhardwaj et al. 2022, Torres et al. 2017). Furthermore, synthetic fertilizers contribute to greenhouse gas emissions during both field application and their energy-intensive production, with agriculture being a major global emitter partially due to fertilizer use. Plant biostimulants improve nutrient use efficiency by enhancing plants' ability to absorb, translocate, and assimilate vital nutrients. Components like humic substances, protein hydrolysates, and microbial inoculants promote root development and activate nutrient transporter systems, allowing crops to achieve similar yields with less synthetic fertilizer. This supports better nutrient management and reduces environmental impacts. Biostimulants may also help lower greenhouse gas emissions, particularly nitrous oxide (N_2O), by increasing nutrient efficiency and decreasing dependence on synthetic fertilizers. Additionally, healthier soils and microbial activity facilitated by biostimulants may boost soil carbon sequestration, aligning with climate-smart agricultural strategies.

Biostimulants as a Sustainable Agricultural Input: In response to the rising environmental concerns associated with chemical fertilizers, biostimulants have become a sustainable alternative. These products, including seaweed extracts, humic acids, amino acids, and beneficial microbes, are designed to promote plant growth, improve nutrient absorption, and increase resilience to abiotic stresses without serving as direct nutrient sources. By stimulating soil microbial activity, enhancing nutrient bioavailability, and supporting overall plant health, biostimulants improve nutrient use efficiency. Research shows that biostimulants can decrease reliance on synthetic fertilizers, reduce environmental harm, and aid in soil restoration. Their use is especially prevalent in organic farming and integrated pest management, where reducing chemical inputs is a key goal. With consumer demand for environmentally friendly food and a global movement toward sustainable agriculture, the biostimulant market is expected to expand rapidly in the coming years (Rouphael & Colla 2020a, 2020b).

Balancing Productivity and Sustainability: The complex global challenge involves the interaction of population dynamics, economic development, land use, fertilizer dependence, and environmental sustainability. As the population increases and demand for agricultural products rises, pressure on arable land and limited natural resources will escalate. Although fertilizers have been key to meeting past and present food production needs, their environmental drawbacks highlight the importance of alternative and supplementary strategies. Biostimulants present a promising solution by boosting productivity in a more sustainable and ecologically friendly manner. Future farming systems must embrace innovative, integrated approaches that reconcile the urgent need for higher yields with the long-term responsibility of environmental preservation. Achieving this will depend on interdisciplinary efforts across agronomy, environmental science, economics, and policy to develop resilient, efficient, and sustainable global food systems (Baltazar et al. 2021, Roche et al. 2024).

2.10. Role of Biostimulants in Sustainability Goals

Biostimulants and Sustainable Food Systems: Sustainable food systems are crafted to ensure sufficient food production for a growing global population while actively minimizing environmental harm, protecting biodiversity, and preserving long-term ecological health. Enzyme- and microorganism-based biostimulants play a crucial role in achieving these goals by promoting soil vitality, enhancing nutrient efficiency, and decreasing reliance on synthetic chemical inputs.

Enhancing Soil Health and Fertility: Microbial communities are essential for sustaining soil health by fostering microbial diversity and supporting nutrient cycling. Beneficial microbes, such as nitrogen-fixing bacteria and phosphate-

solubilizing fungi, improve the availability of vital nutrients to plants, reducing the dependence on synthetic fertilizers. Enzyme-based biostimulants further aid this process by breaking down organic matter and releasing important nutrients like nitrogen, phosphorus, and potassium into the soil. These enhancements in nutrient accessibility not only boost soil fertility but also improve soil structure, increasing its resistance to erosion, compaction, and degradation (Selvan et al. 2023, Gomiero et al. 2011).

Reduction in Chemical Inputs: The application of enzyme- and microorganism-based biostimulants can markedly decrease the dependence of the agriculture sector on chemical fertilizers and pesticides. By enhancing nutrient absorption and improving plant vitality, these biostimulants offer natural alternatives to traditional agrochemicals. Beneficial microbes, such as Bacillus and Trichoderma species, produce bioactive secondary metabolites that provide protection against phytopathogens and insect pests. This biological approach to pest and disease control reduces the need for synthetic pesticides, supporting environmentally sustainable farming practices and reducing the ecological impact of food production systems (Saleem et al. 2024, Ansari et al. 2024).

Soil Microbiome Management: Targeted application of microorganism-based biostimulants can actively modulate the soil microbiome to favor more beneficial microbial communities. This form of ecological engineering in the rhizosphere promotes enhanced plant growth and greater stress resilience, while supporting agroecosystems aligned with sustainable farming principles. By modulating the microbiome, enzyme- and microorganism-based biostimulants facilitate the development of low-input agricultural systems that sustain productivity without jeopardizing long-term soil health and ecosystem functions (Khoso et al. 2024, Ehinmitan et al. 2024). The use of biostimulants positively impacts soil microbial communities by encouraging the proliferation and activity of beneficial microorganisms in the rhizosphere. Microbial biostimulants like plant growth–promoting rhizobacteria (PGPR) and mycorrhizal fungi enhance nutrient cycling, organic matter decomposition, and the production of growth-promoting metabolites. An increase in microbial diversity not only supports plant health but also reinforces ecosystem stability and resilience in agricultural soils.

Waste Bioremediation: Bioremediation, supported by specific microorganisms, has become a highly effective strategy for managing industrial waste. Microorganisms capable of breaking down organic pollutants are now commonly used to treat environmental contaminants such as oil spills and toxic industrial effluents. Simultaneously, enzyme-based biostimulants are employed to accelerate the decomposition of organic compounds in wastewater systems, thereby decreasing dependence on hazardous chemical treatments. The use of these biological agents in waste management not only promotes cleaner production processes but also advances broader objectives of environmental compliance and sustainable industrial development.

2.11. Improved Soil Health Indicators

Biostimulants have been demonstrated to enhance several crucial soil health indicators, such as soil organic matter, enzymatic activity, and soil structure. By promoting microbial processes and root exudation, biostimulants aid in improving soil aggregation, water retention, and nutrient availability. These positive changes in the soil's physical, chemical, and biological properties support long-term soil fertility and sustainable crop production.

Biodegradable Materials: Ongoing research and application of enzyme- and microorganism-based biostimulants have expanded into the development of biodegradable materials. Specific microbial species produce biopolymers that serve as sustainable alternatives to traditional, petroleum-based plastics. For instance, enzymes like polyhydroxyalkanoate (PHA) synthases facilitate the production of bioplastics that are naturally biodegradable. These materials contribute to reducing the buildup of persistent plastic waste in the environment, providing a practical pathway toward more circular and less polluting material life cycles (Ranjithkumar 2025, Thwaites et al. 2025).

2.12. Global Market Overview

The global biostimulants market was valued at USD 2,982.9 million in 2022 and is projected to reach USD 6,849.8 million by 2030, growing at a compound annual growth rate (CAGR) of 11.19% from 2023 to 2030. Another forecast estimates the market will attain USD 5.4 billion by 2027, with a CAGR of 10.2% between 2022 and 2027, highlighting the sector's strong expansion (Meena et al. 2025, Chakrabarty & Selvakumaran 2025, Jankuloska et al. 2025).

Key market players include 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, among others actively engaged in biostimulant production. 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 market's highly competitive and fragmented landscape (Khoulati et al. 2025b, Rouphael & Colla 2020a, 2020b, Sible et al. 2021).

The sector's growth is predominantly driven by the increasing focus on sustainable agriculture, heightened farmer

awareness of biostimulants' role in improving yield and quality, and rising demand for organic products. Additionally, there is a significant need to lessen environmental impacts by adopting alternatives to chemical fertilizers. These factors are supported by technological advancements that produce new formulations with enhanced effectiveness and crop-specific benefits, along with regulatory frameworks that increasingly endorse sustainable practices (Khoulati et al. 2025a). The implementation of precision agriculture underscores biostimulants' importance in maximizing nutrient efficiency and enhancing plant resilience. Consumer preferences for organic and sustainably produced foods further contribute to market growth, while digital technologies facilitate precise application methods and data-driven decision-making. Furthermore, collaborations between manufacturers and stakeholders are driving the development of region- and crop-specific solutions.

Segmentation of the global market provides further insight (Table 1). 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 segment, 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).

Regional analysis highlights the substantial growth and variation across the foremost geographical markets. Europe accounted for nearly 31% of the global biostimulants market in 2021, indicating the significant adoption of organic farming practices and supportive EU agricultural policies. On the other hand, market assessment as per the year 2022, the Asia-Pacific region signifies 38.67% of the global market, which is equivalent to USD 1,153.5 million, following its expansion linked to expanded population, rising in food demand, government initiatives, and mounting awareness of sustainable agricultural practices. In addition, North America establishes a vital regional market. Considering these regional estimates parallel to different years and may reflect different market valuations, the reported shares should be interpreted within their corresponding source years rather than as a direct comparison of regional rankings (Critchley et al. 2021; Mandal et al. 2023; Khoulati et al. 2025b; Naikoo et al. 2025).

Competitive strategies within the sector encompass partnerships, mergers and acquisitions, product innovations, and joint ventures. Companies continue to prioritize investments in research and development, capacity expansion, and supply chain optimization to enhance their competitive position. As reflected in reports like the "Biostimulants Market – Forecast (2022–2027)" by Industry ARC, the segmentation is extensive, including factors such as form (dry, liquid), product type (microbial vs. nonmicrobial), application method (foliar, soil, seed treatment), crop type (cereals, fruits, vegetables, plantation crops, turf and landscape), and detailed country-level geographies.

Several structural factors drive this market's growth. Globally, organic farmland is expanding, as indicated by FiBL statistics, while food demand continues to rise despite limited arable land. FAO data reveal a 53% increase in primary crop production from 2000 to 2019, reaching 9.4 billion tonnes, and OECD projections suggest that future improvements will

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	Leading 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

depend heavily on yield enhancements. Biostimulants are emerging as crucial enablers of this yield increase.

Challenges persist, especially with unorganized and local producers offering low-quality products that harm farmer confidence and tarnish the reputation of established brands. However, the outlook remains promising. Recent developments demonstrate ongoing momentum, such as UPL AgroSolutions Canada's approval of the OHM biostimulant (2021), UPL Australia's launch of GoActiv Technology (2021), and Acadian Seaplants Ltd.'s introduction of seaweed-based biostimulants (Acadian BioSwitch™) in India, aimed at improving germination, yield, and weed suppression (Khoulati et al. 2025a, Naikoo et al. 2025).

2.13. Indian Biostimulants Market

The biostimulants sector is experiencing rapid global growth, with particular emphasis on the Indian context (Table 2). India's extensive agricultural base, unique growth patterns, and emerging policy frameworks make its market especially noteworthy (Naikoo et al. 2025). Valued at USD 79.2 million in 2022, the Indian biostimulants market is expected to reach USD 189.7 million by 2030, expanding at a robust CAGR of 11.5% from 2023 to 2030. While accounting for only about 3% of the global market in 2022, India is the fastest-growing market in the Asia-Pacific region, underscoring its increasing significance on the world stage. The market is segmented by active ingredients, with acid-based biostimulants leading, generating 48.11% of revenue in 2022 (Indian Chamber of Commerce 2023, IMARC Group 2024). Their popularity arises from their capacity to enhance nutrient absorption, improve soil fertility, and bolster plant resilience under stress. Concurrently, seaweed extracts represent the fastest-growing segment, driven by the rising adoption of organic farming practices and their alignment with sustainable crop production systems. Additionally, microbial-based and mixed active ingredient formulations are experiencing steady growth as farmers adopt modern techniques that incorporate biological inputs into conventional farming.

Several factors underpin this robust growth. India's expanding population, increasing consumer preference for organic and environmentally friendly food products, and rising purchasing power are driving demand for safe, high-quality produce. Farmers are also adopting biostimulants as effective alternatives to chemical fertilizers, indicating greater awareness of their long-term benefits for crop yield and soil health. At the same time, modernization of agricultural techniques and the customization of products by Indian companies such as Biostadt India Limited to suit specific crop and soil types are further accelerating adoption.

However, challenges persist in this fragmented market. Numerous local and unorganized players compete with established companies, often by offering low-quality, low-cost products. This situation impacts pricing dynamics and undermines farmer confidence and brand credibility for premium products. Nonetheless, larger domestic players such as Rallis India Limited and UPL Ltd., along with multinational corporations like BASF SE, Isagro, Novozymes, Koppert, and others, continue to strengthen their market presence through innovation, expanded distribution networks, and crop-specific product development.

Looking ahead, India's biostimulants market is poised to become one of the fastest-growing globally, even as China is projected to become the revenue leader in the Asia-Pacific region by 2030. With a growing consumer base, government backing for sustainable agriculture, and rising private-sector innovation, India is expected to play a crucial role in shaping the region's biostimulant industry.

2.14. Experimental Challenges in Evaluating Biostimulants

Experimental challenges in biostimulant research arise from their complex composition, variable effects, and the lack

Table 2: 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

of standardized testing methods. Biostimulants, defined as substances or microorganisms that enhance plant metabolic processes without serving as direct sources of nutrients or pesticides, are increasingly used in sustainable agriculture, stress mitigation, and nutrient efficiency improvements (Baltazar et al. 2021, Yakhin et al. 2017, Delaeter et al. 2024). However, their heterogeneous formulations, particularly those derived from natural sources such as seaweed extracts, humic substances, and protein hydrolysates, hinder effective characterization (Bhupenchandra et al. 2020). Their composition can vary substantially based on source material, extraction, and processing methods, leading to batch-to-batch variability that challenges reproducibility and standardization. Additionally, these products exhibit complex biological activities, containing multiple active molecules or microbial communities. This complexity complicates the attribution of specific effects to individual components and makes it difficult to discern synergistic or antagonistic interactions among constituents. A significant obstacle in biostimulant research is the absence of standardized protocols, which hampers consistent results and cross-study comparisons. Unlike pesticides or fertilizers, which adhere to well-established regulatory testing frameworks, biostimulants lack universally accepted guidelines for efficacy assessment (Khoulati et al. 2025b, Sun et al. 2024).

Experimental design encounters reproducibility challenges due to environmental variability and difficulties in scaling from controlled environments to field conditions. Understanding the mode of action of biostimulants remains one of the most complex experimental challenges in this domain. These substances are known to trigger systemic or hormone-like responses in plants, which are hard to trace using traditional physiological techniques. Employing advanced multiomics approaches such as transcriptomics, metabolomics, and proteomics is essential to unravel these complex molecular and biochemical pathways involved. However, these methods are resource-intensive and costly. Additionally, the absence of universal biomolecular markers to verify biostimulant activity complicates the standardization of assessments and the confirmation of mechanisms. The biological complexity combined with limited available methods hinders a clear understanding of how biostimulants function. Regulatory and claim validation obstacles further challenge the proper evaluation and commercialization of biostimulants. Regulations such as EU Regulation 2019/1009 demand robust scientific evidence for product claims, yet no universally accepted testing protocols exist, and overlaps with fertilizers or biopesticides create classification ambiguities.

Data interpretation and meta-analyses in biostimulant research are also hampered by substantial challenges. A major issue is the heterogeneity of published studies, which vary in crop species, product formulations, application rates, experimental designs, and environmental conditions. This variability complicates data integration and limits the ability to conduct meaningful meta-analyses that produce generalized conclusions about efficacy. These issues underscore the urgent need for rigorous experimental design, standardized methodologies, advanced analytical tools, and close collaboration between regulators and scientists to ensure reliable and meaningful evaluation of biostimulant products.

3. VISION AND FUTURE PERSPECTIVES

Over the past century, the application of synthetic fertilizers and pesticides has significantly increased food production. However, this has also led to nutrient depletion, soil degradation, water pollution, loss of beneficial microbes, greenhouse gas emissions, and elevated costs for farmers. To address these issues, biofertilizers utilizing helpful microbes to enhance nutrient cycling were developed, though their effectiveness often varied depending on farming conditions. This limitation spurred the development of biostimulants, a broader category of products that go beyond mere nutrient supply. Biostimulants include both microbial and nonmicrobial agents that promote plant growth, improve nutrient use efficiency, and increase resilience to abiotic stresses such as drought, salinity, and extreme temperatures, while also enhancing crop quality traits. Their non-toxic nature, minimal ecological persistence, and diverse modes of action position them as key tools in transitioning toward sustainable intensification. Looking forward, biostimulants are set to play a central role in future agricultural systems.

Nonetheless, several research gaps remain. First, their mechanisms of action are often not well understood, with many effects observed empirically but lacking molecular or physiological validation. Second, their performance depends heavily on local conditions across soils, climates, crops, and cultivars, necessitating systematic multi-location, multi-year field trials to ensure consistent results. Third, integrating biostimulants with precision agriculture and digital farming technologies could optimize their application but is still underdeveloped. Fourth, current regulatory frameworks are fragmented and lack harmonization, hindering global adoption and standardization. Finally, most efficacy assessments focus solely on yield; future studies should incorporate economic analyses, input savings, soil health indicators, and ecosystem service evaluations to fully capture their benefits. Addressing these challenges requires an interdisciplinary approach that combines molecular biology, plant physiology, soil science, and agronomy

with socio-economic and policy considerations. At the policy level, harmonized regulations and quality standards are essential to filter out ineffective products and bolster farmer confidence. By closing these gaps, biostimulants can transform from promising innovations into fundamental technologies for achieving sustainable, resilient, and climate-smart agriculture.

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