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BIOSTIMULANTS AND THEIR INFLUENCE ON PLANT DEVELOPMENT. COMPARATIVE DATA ON THE MAIN AGRICULTURAL CROPS

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Abstract

This paper presents a synthesis of a technological alternative with major impact on crop development and environmental protection — the use of biostimulants. Starting from the definition, classification, and market presence of biostimulants, through to the most recent scientific studies and a bibliometric analysis, this work aims to contribute modestly to the vast body of literature on this important yet incompletely explored topic. Many aspects remain unknown regarding their mode of action and quantifiable influence on agricultural production and vegetative growth. The relevance of this topic aligns with the European Commission's "Farm to Fork" strategy, which promotes the reduction of fertilizers and pesticide use, and the identification of new products to enhance plant health and productivity.

***Key words**: biostimulants, climate change,main agricultural crops, plant health productivity*

INTRODUCTION

Currently, biostimulants are considered one of the most promising alternatives to prevent production losses caused by plant stress, exacerbated by climate change. Biostimulants exclude the use of synthetic pesticides and chemical fertilizers, being based on various beneficial plant-derived compounds. These substances aim to increase tolerance to abiotic stress. This paper summarizes the current state of research regarding the influence of biostimulants on plant development and how they can optimize yields under stress conditions caused by climate change (Garcia-Garcia et al., 2020).

Out of the 17 Sustainable Development Goals established globally by the United Nations, Goal 2 — ending hunger by 2030 — ranks among the top. To achieve this, it is necessary to double global food production. Trends indicate a projected 100–110% increase in demand by 2050 (Tilman et al., 2011), yet current production levels are insufficient to meet this need (Ray et al., 2013). According to IPCC reports, global warming of more than 2°C may drastically reduce yields (Hoegh-Guldberg et al., 2018), which is why biostimulants are gaining attention as part of climate-smart agriculture strategies.

Furthermore, in this context, a decline in the nutritional quality of crops is also observed. One of the greatest challenges is feeding a global population projected to reach 9 billion by 2050 (Tilman et al., 2011), against a backdrop of increasing heat waves, abundant precipitation events, and periods of drought, flooding, and heightened salinity (Mba et al., 2012). Zhang and colleagues (2018) highlighted that abiotic stress in plants represents the main cause of severe production losses ranging from 50% to 80%, depending on crop type and geographic region.

BIOSTIMULANT CATEGORIES AND MECHANISMS

To reduce fertilizer dependence, a promising strategy is the application of biostimulants (Bulgari et al., 2019). These act by triggering plants' natural defense mechanisms and enhancing physiological efficiency (Singh et al., 2018; Xu & Geelen, 2018). Biostimulants act solely as triggers of the plant's natural defense mechanisms and are applied in small quantities.

The concept of organic biostimulants (BS) has evolved over time (du Jardin, 2012, 2015b; Traon et al., 2014; Halpern et al., 2015; Yakhin et al., 2017; European Biostimulants Industry Council – EBIC, 2020).

The concept of biostimulants has evolved, and according to EU Regulation 2019/1009, a plant biostimulant is:

"a product that stimulates plant nutrition processes independently of its nutrient content, with the sole aim of improving nutrient use efficiency, tolerance to abiotic stress, crop quality traits, or availability of nutrients in the soil or rhizosphere."

On the other hand, du Jardin (2015a) defined biostimulants as any compound or microorganism used to enhance plant growth, stress response, and/or crop quality, regardless of their nutrient content. Later, the same author emphasized that biotic substances act as modulators of vital processes in plants, enhancing growth and resource-use efficiency both under stress and non-stress conditions (du Jardin et al., 2020).

Du Jardin (2015a) classified biostimulants by origin: humic and fulvic acids, seaweed extracts, protein hydrolysates, beneficial fungi and bacteria, and compounds like amino acids and peptides. These can enhance root growth, nutrient uptake, and tolerance to stress.

Bulgari et al. (2019) argued that this approach does not always provide adequate information regarding the biological activity of these agents.

In modern agriculture, cost-effective strategies are being sought to enhance productivity and support plant development. In this era of biotechnology, plant biostimulants have gained significant momentum, particularly with the transition towards organic farming systems. These biostimulants hold considerable potential for improving plant productivity and stress resilience by reducing dependency on chemical fertilization. However, the mechanisms through which biostimulants exert their effects are not yet fully understood, necessitating further applied research (Kaur et al., 2021).

The European Commission's "Farm to Fork" strategy envisions reducing fertilization inputs, limiting pesticide use, and identifying new products that enhance the developmental and health-related traits of plants (Artyszak & Gozdowski, 2020).

Gonzales-Perez et al. (2022) aimed to elucidate the current state of the use of microalgae-based biostimulants and their application methods in field conditions. The study discussed the use of microalgae in crop production and the benefits of seed treatment, foliar application, soil irrigation, and hydroponic treatments.

The findings highlighted that applying these biostimulants to cultivated plants provides multiple benefits: improved root development, increased yield, enhanced resistance to pathogens, and greater tolerance to drought and salinity. The data indicated that microalgae used as biostimulants are a promising alternative for crop protection and can also function as growth regulators. The authors recommended further investigation, as many microalgae species remain largely unexplored in this domain.

The Genesis Group recently offered a classification system based on seven main categories:

- Natural Organic Substances: Humic and fulvic acids, seaweed extracts
- Beneficial Microorganisms: Rhizobacteria, mycorrhizae
- Phytohormones: Auxins, cytokinins, gibberellins
- Enzymes and Amino Acids: Catalyze biochemical processes, promote growth
- Vitamins and Micronutrients: Zinc, manganese, iron, copper — essential in metabolic regulation, enhancing crop growth and development of cultivated crops.

EXPERIMENTAL FINDINGS

The combined application of biostimulants and selenium has demonstrated that biostimulants play a key role in increasing grain yield per spike and overall biomass (DS), without reducing the total Se content or altering the forms of Se present in the grains. This aligns with the primary objective of biofortification processes.

Alternatively, the use of a biostimulant for plants named Fyto-fitness (BIO Fitos, S.R.O., Czech Republic), based on heteropolyoxometalates and containing Mo, B, Si, W, and V in Keggin structure combined with humic acid, has been proposed as an antistress agent to mitigate selenium-induced phytotoxicity (Xiao et al., 2021).

Although the application of antistress agents is currently a subject of research, few previous studies have explored the potential use of biostimulants in crops subjected to selenium fertilization. While some studies have reported that the use of fulvic acids as biostimulants exerts both beneficial and antagonistic effects depending on selenium dosage (Peng et al., 2001), the authors did not provide specific information regarding the final concentration or chemical forms of selenium in plant tissues. This aspect is critical for evaluating the potential health benefits of biofortification with selenium.

Natural biostimulants mitigate the adverse effects of climatic stress and enhance plant health (Lozowicka et al., 2019). These biostimulants primarily contain humic or fulvic acids, which promote lateral root development and alleviate abiotic stress responses (Anjum et al., 2011). Several studies have also reported the positive impact of biostimulants on grain quality parameters, including protein, starch, gluten, and amino acid content (Nugmanov et al., 2018).

The spring wheat cultivar ‘Mandaryna’ was sown in 4 × 5 m plots in DobrzyniewoDuże, Poland (53°11′43.6″N, 23°01′02.7″E) during the period 2017–2020. Fungicides were applied in recommended doses (F1: Artea 330EC, cyproconazole + propiconazole; F2: Falcon 460EC, spiroxamine + tebuconazole + triadimenol), and in half doses (½ F1; ½ F2), alongside humic acid-based biostimulants aimed at enhancing plant growth (S1: liquid; S2: paste).

The tested variants, each with four replications, were as follows:

A – control;

B – sulfosulfuron;

C – sulfosulfuron + ½ cyproconazole + ½ propiconazole, ½ spiroxamine + ½ tebuconazole + ½ triadimenol;

D – sulfosulfuron, cyproconazole + propiconazole, spiroxamine + tebuconazole + triadimenol;

E – sulfosulfuron, humic biostimulant S1;

F – sulfosulfuron, cyproconazole + propiconazole, spiroxamine + tebuconazole + triadimenol, humic biostimulant S1;

G – biostimulant S1;

H – sulfosulfuron, cyproconazole + propiconazole, spiroxamine + tebuconazole + triadimenol, biostimulant S2.

The effectiveness of chemical and biostimulant-based protection in wheat was influenced by climatic conditions, which resulted in quantitative differences between variants. Chemical protection alone (variant D) or in combination with biostimulant S1 (variants E and F) proved to be the most efficient options for wheat protection, contributing to yield improvement. Consequently, these variants have been recommended in practical agriculture. Variant C (half-dose fungicides) showed similar grain quality parameters to those with full-dose treatments, while leading to higher amino acid concentrations. Therefore, reducing fungicide doses aligns with the objectives of the European Commission's "Farm to Fork" strategy (Iwaniuk et al., 2022).

Currently, there is no universally accepted definition for biostimulants, despite their recognized roles in regulating plant growth and development (Calvo et al., 2014; Halpern et al., 2015). Biostimulants originate from natural sources and are typically categorized into four groups: humic and fulvic acids, microorganisms, plant-derived bioactive substances, and other compounds (du Jardin, 2015; Bhuyan et al., 2020).

Hasanuzzaman et al. (2021), in their study Biostimulants for the Regulation of Reactive Oxygen Species Metabolism in Plants under Abiotic Stress, presented a schematic model that effectively summarizes the aforementioned concepts.

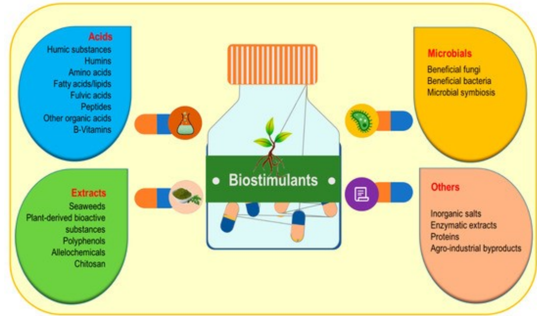

Figure 1. Major categories of biostimulants. (Hasanuzzaman, M., Parvin, K., Bardhan, K., Nahar, K., Anee, T. I., Masud, A. A. C., &Fotopoulos, V. (2021). Biostimulants for the Regulation of Reactive Oxygen Species Metabolism in Plants under Abiotic Stress. *Cells*, *10*(10), 2537. https://doi.org/10.3390/cells10102537)

EFFECTS ON DROUGHT AND SALINITY STRESS

Among the limiting factors of plant development and yield reduction, drought is the primary stressor due to the water requirements of cultivated lands, influenced by increased evapotranspiration associated with climate change (Zhao & Dai, 2015; Kim et al., 2019). Water deficit induces oxidative bursts within plant cells. Stomatal closure caused by drought periods leads to photorespiration, which can account for up to 70% of the water produced in leaves (Noctor et al., 2002).

In many crops, water deficit occurs transiently, and the application of biostimulants is widely used to enhance crop performance under abiotic stress conditions. For instance, the application of humic acid has been shown to enhance enzymatic antioxidant defense, improve drought tolerance, and minimize oxidative stress in plants (Garcia et al., 2012; Arslan et al., 2021). Humic acid is derived from the biodegradation of plant material and microorganisms. It acts directly on plant development and metabolism. Its effects have been documented across numerous agricultural crops and cannot be attributed solely to its hormonal activity (Muscolo et al., 2013).

An increasing body of evidence suggests that the application of biostimulants may represent a cost-effective strategy to mitigate drought-induced oxidative stress and improve crop health under stressful conditions (Hasanuzzaman et al., 2021). In millet exposed to water stress by withholding irrigation at the three- to five-leaf stage, humic acid application stimulated plant growth, affected stomatal conductance, and enhanced photosynthetic activity (Shen et al., 2020).

In drought-affected sugarcane, humic acid helped plants recover from water stress by increasing catalase activity and effectively closing stomata, thereby conserving water within the plant (Aguiar et al., 2016).

Another widely used biostimulant—seaweed extract—is applied across various crops to enhance productivity (Khan et al., 2009; Battacharyya et al., 2015). The commercial extract of Ascophyllum nodosum applied to soybean led to increased water content, reduced wilting, and improved recovery under drought conditions (Shukla et al., 2018).

In field-grown maize, the combined application of humic acid and a sulfur-containing soil amendment significantly increased catalase activity and reduced water loss under drought conditions (Kaya et al., 2020).

Soil microorganisms have also been shown to enhance plant health under stress, and their use has gained relevance as a drought management strategy (Chandra et al., 2021). Microbial inoculants such as Pseudomonas fluorescens and Bacillus amyloliquefaciens increased antioxidant accumulation in mint (Chiappero et al., 2019).

In cooler regions of Europe, winter pea cultivation relies heavily on proper plant development before winter. Previous research suggests that plants must develop short internodes and at least the first two leaves before frost occurs. This developmental stage is often not reached, primarily due to delayed sowing caused

An effective solution may involve the pre-sowing application of plant growth regulators. Klimek-Kopyra and colleagues (2019) evaluated the developmental characteristics of winter pea plants in response to biostimulant applications under low temperature conditions (4°C). Seven different winter pea cultivars were treated with three biostimulants: Asahi SL, Kelpak SL, and Primus B. After 21 days of early plant development, shoot and root length and biomass were measured. It was found that the cultivars ‘Enduro’ and ‘Aviron’ exhibited the most significant root development, regardless of the applied biostimulant. The highest germination rate was recorded in the ‘Aviron’ cultivar.

The authors concluded that, for autumn-sown peas, the efficacy of biostimulants on the tested cultivars was generally low. Slightly improved results were observed for the Asahi SL biostimulant, particularly in the previously mentioned cultivars.

CASE STUDIES ON MAIN AGRICULTURAL CROPS

Recently, in pea crops, Kamran et al. (2023) investigated the optimal dosages of two biostimulants aimed at enhancing Rhizobium activity, root growth, nodulation capacity, NPK uptake, yield, and overall quality. The study’s findings suggested that the combined application of fulvic acid and ascorbic acid at concentrations of 200 ppm proved more effective than individual applications. Notable improvements were observed in vegetative growth, as indicated by a significant increase in the number of pods per plant, fresh and dry pod biomass per plant, number of seeds per pod, total chlorophyll content, carotenoids, and macronutrient levels in pea seeds, including nitrogen (16.17%), phosphorus (40.47%), potassium (39.96%), and protein content (16.25%). Optimal doses (200 ppm) should be maintained, as excessive concentrations may inhibit nitrogen fixation by Rhizobium through interference with nitrogenase enzyme activity.

The aim of the study conducted by Niewiadomska et al. (2019) was to evaluate the influence of two selected biostimulants (Tytanit, Rooter) and six foliar fertilizers (Optysil, Potassium Metalosate, Bolero Bo, ADOB 2.0 Zn IDHA, ADOB B, ADOB 2.0 Mo) on the enzymatic activities of dehydrogenase, acid and alkaline phosphatases, and catalase, as well as their impact on the level of biological nitrogen fixation based on nitrogenase activity in soybean crops. Between 2016 and 2018, a field experiment was conducted at the Experimental and Educational Station in Gorzyń, University of Life Sciences in Poznań, Poland.

Over the three experimental years, foliar fertilizers and biostimulants significantly stimulated the catalytic activity of dehydrogenase (DHA) and alkaline phosphatase (PAL) across all experimental treatments, compared to the control. Analysis of acid phosphatase (PAC) activity during the soybean growth period revealed a significant decrease compared to the control in treatments with Tytanit, Rooter, and Bolero Mo. Additionally, catalase (CAT) activity analysis showed that, apart from Tytanit, all products significantly stimulated this enzyme relative to the control. Field analyses of biological nitrogen fixation demonstrated that both foliar fertilizers and biostimulants significantly enhanced nitrogenase activity in soybean crops.

Szczepanek and Siwik-Ziomek (2019) assessed phosphorus and potassium accumulation in autumn-sown rapeseed following the application of a biostimulant under varying NPK and sulfur fertilization levels. The factors examined included two NPK fertilization rates—high (180 N, 70 P, 132 K kg ha^{-1}) and low (144 N, 35 P, 66 K kg ha^{-1}); elemental sulfur fertilization (36 or 0 kg ha^{-1}); and seaweed-based biostimulant application (with or without treatment). The biostimulant increased P and K accumulation in rapeseed stems during the generative growth phase. Application of the biostimulant in treatments with reduced NPK or no sulfur fertilization enhanced stem P and K content to levels comparable to those achieved with higher NPK and sulfur doses without the biostimulant. Increasing NPK fertilization led to greater P and K accumulation in both stems and roots during flowering and maturation stages. The highest increase in P and K uptake per 1000 kg of seeds was achieved through the application of the biostimulant.

Over the decades, researchers have increasingly focused on physiologically active substances of natural origin applied in extremely low doses (Jelev &Dascaliuc, 2018). Their mode of action is directed toward activating and sustaining vital physiological processes in plants. These compounds stimulate growth processes through vigorous root formation and induce plant immunity, thereby improving plant adaptation to adverse environmental factors. As a result, crop productivity is enhanced, product quality is improved, and production costs are reduced.

GERMINATION AND PHYSIOLOGICAL EFFECTS

The aim of the research conducted by Luțcan et al. (2024) was to assess the physiological characteristics of food-grade maize germination influenced by a natural extract of biologically active substances (JS), derived from the plant Juniperus sabina L., and to evaluate the combined impact of high temperature and JS treatment. The study analyzed seeds from three food-grade maize hybrids: super-sweet Porumbeni 300 (P300), popcorn Porumbeni 398 (P398), and flour maize Porumbeni 402 (P402), developed at the “Porumbeni” Institute of

Phytotechnics, and a coniferous plant extract (JS) from Juniperus sabina L. (Elisovetcaia et al., 2019; Luțcan et al., 2024).

Maize seeds (25 per replicate, 4 replicates) were soaked in a 0.0001% JS extract solution or in water (control, untreated seeds) for 24 hours, then subjected to heat stress at 50°C for 30 minutes. Germination of both intact, stressed, and JS-treated seeds was conducted in accordance with international seed testing standards (ISTA, 2017). After 7 days, germination capacity was assessed, biometric measurements (radicle and plumule lengths) were performed, and dry biomass of separated seedling components (root mass, shoot mass, and remaining seed) was evaluated. The mobilized reserve substances for respiration and the metabolic efficiency of germinating seeds were calculated (Dascaliuc et al., 2020; Ivanova et al., 2022).

Initial germination capacity was relatively high, ranging from 87–93%. Treatment with the JS plant extract reduced germination by an average of 11.2% in the P300 super-sweet hybrid, had no effect on popcorn hybrid P398, and enhanced germination in hybrid P402 by 6.5%. These findings highlight the differential response of maize hybrids to the JS extract and underscore the importance of species and biostimulant specificity in applying plant-derived bioregulators (Luțcan et al., 2024).

Wheat, as a staple crop, faces numerous challenges due to climate change and the increasing demand for sustainable practices. Biostimulants, which enhance plant growth and stress resilience, have gained attention for their potential to improve wheat productivity in an environmentally friendly manner. In 2025, a research team conducted a comprehensive bibliometric analysis of field-based studies on wheat response to biostimulants from 2000 to 2024.

Analyzing 222 studies, the bibliometric review revealed a significant rise in research publications on biostimulants, with an annual growth rate of 15.6%. Asia led in publication output (59.4%), followed by Europe (18.1%) and Africa (11.6%). North America, South America, and Oceania had fewer contributions. Additionally, institutions from Pakistan, India, and Egypt ranked as the most productive in this field, while Saudi Arabia stood out with the highest rate of international collaboration—91.7% among countries and 100% among institutions.

The studies concluded that biostimulants significantly improve wheat's tolerance to abiotic stress, enhance nutrient uptake, and promote overall plant health. Research is shifting from traditional organic methods and microbial inoculants toward advanced biostimulant formulations, improved nutrient management, and reduced environmental impact. However, gaps remain, particularly in understanding the combined effects of multiple biostimulants and their long-term impact on wheat and soil health. This synthesis of research trends lays the groundwork for promoting sustainable wheat production, ensuring food security, and enhancing agricultural resilience in the face of environmental challenges (Sellami et al., 2025).

As previously highlighted, wheat is a key global crop, and environmentally safe tools are essential to cope with major agricultural stressors. Melatonin is considered a universal molecule with plant growth-regulating properties and multiple roles, including its use as a biostimulant against plant stress factors. In an experiment on two Bulgarian wheat varieties (Fermer and Gines), melatonin supplementation at 75 µM via root application was tested. Evaluation of selected stress markers, including malondialdehyde, along with phenotypic characteristics, demonstrated that this treatment did not impair the physiological responses of the plants (Katerova et al., 2024).

Between 2012–2013, Popko et al. (2018) conducted field and laboratory experiments to evaluate the effects of new amino acid-based plant growth stimulants on yield, grain characteristics, and macro- and micronutrient content in winter wheat (Triticum aestivum L.). Two formulations developed in collaboration with INTERMAG Co. (Olkusz, Poland)—AminoPrim and AminoHort—were tested, containing 15% and 20% amino acids, respectively, and 0.27% and 2.1% microelements.

Field trials showed that amino acid-based product application increased wheat yield by 5.4% (AminoPrim, 1.0 L/ha) and 11% (AminoHort, 1.25 L/ha) compared to the untreated control. Laboratory tests indicated improved grain quality indicators such as ash content, Zeleny sedimentation index, and protein content. These preparations also raised micronutrient concentrations, particularly copper (by 31–50%), molybdenum (3.9–16%), and calcium (4.3–7.9%). The study concluded that amino acid-based biostimulants are effective tools for enhancing crop productivity.

To assess the potential for environmental pollution reduction, Abbas et al. (2022) designed a study to test the effect of using compost and biostimulants as full or partial replacements for mineral nitrogen on grain yield and quality in two wheat varieties. Two experiments were conducted over two consecutive growing seasons (2016/2017 and 2017/2018) at the Desert Experimental Station, Cairo University.

Four fertilization treatments (100% mineral nitrogen as control, 100% compost, 75% compost + 25% mineral N, and 50% compost + 50% mineral N) and four foliar biostimulant treatments with VIUSID® agro (control, 0.75, 1.13, and 1.5 L ha^{-1}) were tested on two wheat varieties: Egyptian Gemmiza-10 and Nigerian LacriWhit-4. The 50% compost + 50% mineral N treatment combined with 1.5 L/ha of VIUSID® agro significantly increased grain yield by 0.9 and 1.36 t/ha, respectively.

Application of 100% compost significantly improved grain protein, crude fiber, total sugars, Mg, and Mn content, while 100% mineral nitrogen significantly enhanced ash, total phenols, P, and Ca. Compost substitution also significantly increased ether extract and carbohydrate content in LacriWhit-4 and raised N, K, and Fe content in both varieties. Foliar application of VIUSID® agro biostimulant significantly increased protein, carbohydrate, total sugar, P, K, Ca, Cu, and Zn concentrations. This study supports the use of combined compost and mineral N (50:50) with VIUSID® agro (1.5 L/ha) to enhance both grain yield and quality while mitigating environmental impact.

The objective of the study by Gendaszewska et al. (2025) was to evaluate the combined effects of plant growth stimulants—specifically protein hydrolysates derived from animal waste—and the fungicide azoxystrobin on winter wheat (Triticum aestivum L.). Three formulations were tested: collagen hydrolysate with sodium salicylate, collagen hydrolysate with titanium ascorbate, and collagen-keratin hydrolysates with sodium salicylate. These hydrolysates were obtained from tannery waste, especially chromium-treated leather waste, forming part of a circular economy strategy within the leather industry.

Growth vessel experiments revealed that these novel products, when combined with fungicides, increased seedling length by 9.6%, 10%, and 15.9%, respectively, and enhanced fresh biomass by 8.5%, 7.9%, and 9%, compared to the untreated control. Use of collagen and keratin hydrolysates with sodium salicylate also increased the nutrient and amino acid content in the plants.

Spada et al. (2024) reported that following foliar application of two biostimulants, biometric measurements revealed that the root system—crucial for water and nutrient absorption and supporting aboveground growth—developed thicker (larger diameter) but shorter roots in both tested genotypes (Svems16 and Iride). Additionally, biostimulant application reduced root tip number in the first genotype, while increasing it in the second. The increase in root number may reflect enhanced nutrient uptake, as previously indicated by Ristova and Busch (2014).

Such outcomes align with the general expectation that biostimulants affect plant growth dynamics (Majkowska-Gadomska et al., 2021; Wise et al., 2024).

CONCLUSIONS

Biostimulants play a growing role in sustainable agriculture. They optimize plant nutrition, enhance abiotic stress tolerance, and improve crop quality. Their integration into standard agricultural practice supports the European "Green Deal" and global goals for climate-resilient food production. Continued interdisciplinary research is essential to better understand their mechanisms and adapt their use to specific crop and environmental conditions.

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