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Biostimulants and Their Role in Improving the Growth and Yield of Maize under Drought and Salinity Conditions: A Scientific Review

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Abstract

Abiotic stresses such as drought and salinity have been increasing as a limitation to maize (*Zea mays* L.) productivity because these abiotic stressors affect water relations, photosynthesis, ion homeostasis, nutrient acquisition, oxidative balance and ultimate yield development. Here, plant biostimulants have become a promising aspect of climate-resilient crop management since it can lead to increased tolerance to stress without being used as a mere conventional fertilizer. The current review critically evaluates recent findings of the role of biostimulants to enhance maize growth and yield during drought and salinity, focusing on microbial-based biostimulants, humic and fulvic compounds, seaweed- and algae-derived biostimulants, amino acid- and protein hydrolysate-based biostimulants, and chitosan-based bi The existing maize literature reveals that the most reliable advantages are related to enhanced root development, enhanced relative water status, stabilization of photosynthetic activity, enhanced antioxidant defense, osmotic adjustment, and under salinity, enhanced ion selectivity and rhizosphere activity. Microbial inoculants and humic/ulvic compounds and seaweed extracts demonstrate the highest level of maize-specific evidence, with amino acid/protein hydrolysate and nano-enabled methods showing promise but not as well validated under field stress. Although the positive responses were repeated, the review also indicates that the effectiveness of the treatment is genotype-dependent, stress-dependent, and time and formulation-dependent, in addition to being dependent on the interaction with soil conditions. Hence, biostimulants cannot be viewed as a universal yield enhancer; rather, they are a situational physiological aid that can aid nutrient and water management in maize. Future developments need enhanced standardization, increased multi-location field experiments and more explicit mechanistic connection of product composition and maize reaction to a single and combined set of abiotic stresses.

Keywords: *biostimulants, maize, drought stress, salinity stress, seaweed extract, humic acid, fulvic acid, microbial inoculants, yield, abiotic stress.*

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Introduction

Maize is a strategic food, feed, and industry cereal crop but its production is becoming susceptible to variable water, increasing evaporation demand, and advancing soil salinization. In such circumstances, it

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cannot be successfully relied solely on the traditional application of mineral fertilizers to protect the crop performance, particularly in cases where the main constraint is not the inadequacy of nutrients but the stress physiology. The latest reviews have thus framed plant biostimulants as a valuable complementary solution to stress-resilient agriculture since it can positively affect nutrient use efficiency, plant vigor, root-soil interaction, and tolerance to abiotic stress and does not fit the category of its nutrient content (Franzoni et al., 2022; Rakkammal et al., 2023).

Maize is now one of the most instructive systems of assessing realistic biostimulant performance among major field crops. A recent systematic review specifically focused on maize found that biostimulants tend to increase grain yield more reliably than grain quality, but also found significant differences between products, sites and strategies of application. The importance of this finding to agronomic interpretation is that biostimulants can be extremely useful in maize, but their actions cannot always be reproduced and must be interpreted in the context of formulation, timing, environment, and crop management (Ocwa et al., 2024).

The current review was done to synthesize the existing scientific evidence on the effectiveness of biostimulants in enhancing the growth and yield of maize under drought and salinity conditions. Recent evidence, particularly since 2020, is highlighted, along with mechanisms of action, the key classes of biostimulants, studies on maize, agronomic implications, and gaps in research. This way, the review takes on the tone of a scientific article: the authors emphasize the potential of biostimulants but also understand the absence of standardization, the complexity of the stress, and validation in the field (Liaqat et al., 2025).

Drought and Salinity as Major Constraints to Maize Growth and Yield

Maize is impaired by drought and salinity via some overlapping pathways that are physiologically distinct. Drought decreases soil water levels, diminishes the water potential of leaves, constrains cell growth, stomataceae and assimilate synthesis in vegetative and reproductive phases. Salinity starts with an osmotic part, which is equivalent to drought, however, later on, it incorporates ion toxicity, nutrient imbalance, and metabolic dysfunctions related to excess of Na+ and Cl in plant tissues. Maize, in both instances, tends to experience a decrease in root-shoot growth ratio, diminished chlorophyll stability, membrane damage, and poor grain set in case stress is associated with sensitive development phases (Rakkammal et al., 2023; Franzoni et al., 2022).

The constraints can be seen through maize-specific studies. Maize was treated with humic acid under drought, which showed significant growth, photosynthesis, osmolytes, and hormonal regulation differences compared to the untreated stressed plants, which validates that stress alone has a strong disruptive effect on various physiological systems prior to mitigation measures (Chen et al., 2022). Under salinity, seaweed- and microbe-based studies similarly reported marked decreases in dry matter, membrane stability, and photosynthetic traits in untreated maize, while treated plants partly recovered those losses (Pienaar et al., 2025).

A particularly important scientific point is that most biostimulant studies in maize still examine drought or salinity separately, whereas combined drought-salinity stress remains far less explored. This matters because the coexistence of water deficit and salt accumulation is agronomically realistic in arid and semi-arid systems. Therefore, even though current evidence strongly supports the usefulness of biostimulants under each stress individually, the literature base for combined-stress prediction is still limited and should be interpreted cautiously (Ocwa et al., 2024).

Plant Biostimulants: Concept, Classification, and Agronomic Relevance

Modern biostimulant science defines these products by function rather than by traditional fertilizer logic. Their main role is to stimulate natural plant and soil processes that improve nutrient use efficiency, tolerance to abiotic stress, quality traits, and/or nutrient availability in the rhizosphere. Consequently, biostimulants constitute a broad functional group rather than a single chemical class. Current reviews commonly classify them into microbial biostimulants (such as plant growth-promoting bacteria and arbuscular mycorrhizal fungi) and non-microbial biostimulants including humic substances, fulvic acids, seaweed extracts, microalgal products, protein hydrolysates, amino acid formulations, chitosan-based materials, and related complex natural products (Sun et al., 2024).

Such functional diversity is very applicable in agronomy of maize since various biostimulants act on various physiological bottlenecks. Microbial products tend to strengthen the trapping of nutrients, hormonal cues, rhizosphere dynamics, and soil aggregation. Humic and fulvic compounds are likely to have an impact on root morphology, membrane transport, nutrient uptake, and the osmotic adjustment. Seaweed extracts often are mediated by global metabolic reprogramming, such as antioxidant reactions and stress-related pathways. The effects of amino acid, protein hydrolysate, and chitosan-based formulations are usually evident in the early vigor, stress signaling, enzymatic defense, and carbon-nitrogen metabolism. Consequently, to choose a suitable biostimulant to maize when drought or salinity occurs, it is essential to consider both the stress condition and the biological capabilities of the product line (Abdelkader et al., 2025).

Meanwhile, one of the key scientific issues in the area is that biostimulants are also too generally discussed. A product with a very different chemical make-up, microbial viability, extraction history or bioactive concentration can be placed in the same category. One cause of this heterogeneity is the reason that field results can differ significantly across trials, even when products are being marketed or subjected to the same commercial or biological name. The problem is particularly significant in maize where the severity of stress, the type of hybrid, the nature of soil, and the stage of development have a strong influence on the product performance (Ocwa et al., 2024).

Table 1. Major classes of Biostimulants Relevant to Maize under Drought and Salinity

Biostimulant class	Representative examples in maize	Main stress-mitigation mechanisms	Typical application route
Microbial biostimulants	PGPR, Bacillus spp., AMF, microbial consortia	Root colonization; nutrient capture; hormone modulation; osmotic adjustment; rhizosphere activation; ion balance under salinity	Seed inoculation, soil inoculation, seed coating
Humic and fulvic substances	Humic acid, leonardite-derived products, low-MW fulvic acid	Root development; membrane transport; photosynthetic support; osmolyte accumulation; nutrient use efficiency	Seed treatment, soil application, fertigation, foliar spray
Seaweed and algal biostimulants	Kappaphycus alvarezii, Ecklonia maxima, microalgae-based products	Antioxidant activation; metabolic reprogramming; stomatal and photosynthetic protection; stress signaling	Foliar spray, soil drench, seed treatment
Amino acids / protein hydrolysates	Amino acid blends, protein hydrolysate formulations, trehalose-related organic stimulants	N metabolism support; enzyme protection; osmotic buffering; recovery of growth metabolism	Seed priming, foliar spray
Chitosan and nano-enabled products	Chitosan coatings, O-carboxymethyl chitosan nanoparticles, chitosan–fulvic nanocomposites	ROS detoxification; membrane stabilization; gene-expression changes; improved seedling vigor	Seed coating, foliar spray, nano-delivery systems

Mechanisms by Which Biostimulants Improve Maize Tolerance to Drought and Salinity

Bio stimulants enhance stress tolerance in maize using a combination of morphological, physiological, biochemical and molecular functions as opposed to a single mechanism. One recurrent theme in the recent literature is that good products assist in sustaining plant activity during stressful conditions but do not necessarily spur growth in favorable conditions. That is why the enhancement of root architecture, water relations, antioxidant metabolism, and source-sink stability gains more significance than the short-term increment in plant height (Kumar et al., 2020).

Root growth, water uptake, and hydraulic adjustment

Root system reinforcement is one of the most consistent responses reported in maize biostimulant studies. Under drought, humic acid increased root-associated traits and contributed to better plant water management while also modifying hormonal and osmolyte patterns (Chen et al., 2022). Fulvic acid has also been associated with enhanced root development and improved nitrogen metabolism in maize, supporting the view that root stimulation is one of the primary gateways through which biostimulants stabilize stressed plants (Li et al., 2024).

Microbial biostimulants are particularly important in this respect because they extend rhizosphere functionality. In saline maize, the combination of growth-promoting bacteria and arbuscular mycorrhizal fungi enhanced tolerance by strengthening root-associated acquisition processes and reducing stress burden on the plant system (de Carvalho Neta et al., 2024). Similarly, in saline–alkali soils, AMF application increased maize root length, root surface area, and yield while also improving soil nutrient status and microbial community structure (Fan et al., 2024).

Table 2. Representative Recent Studies on Maize Biostimulants under Drought or Drought-Related Stress

Study	Biostimulant	Stress condition	Main maize response
Kaya et al. (2020)	Sulfur-enriched leonardite and humic acid	Drought + P deficiency	Enhanced tolerance and better growth performance under combined resource stress
Kumar et al. (2020)	Kappaphycus seaweed extract	Soil moisture stress	Transcriptional changes in maize roots linked with improved drought resilience
Chen et al. (2022)	Humic acid	Drought	Improved growth, photosynthesis, hormone balance, and osmolyte regulation
Tinte et al. (2022)	Seaweed extract-based biostimulant	Drought	Metabolic reprogramming associated with better stress adaptation
Abdo et al. (2022)	Growth stimulants with biological fertilization strategy	Field conditions / stress-relevant agronomy	Supported maize productivity while reducing chemical dependence
Li et al. (2022a)	Trehalose, compared with chitosan, humic acid, and GABA	Field maize	Trehalose showed superior growth-promoting effect among tested stimulants
Lephatsi et al. (2022)	Microbial biostimulant	Drought	Growth enhancement, priming effects, and molecular drought tolerance responses
Brown et al. (2024)	Chitosan-fulvic acid nanoparticles	Drought	Enhanced antioxidant defense and transcriptional reprogramming
Wu et al. (2024)	O-carboxymethyl chitosan nanoparticles	Water stress	Improved maize seedling tolerance to water deficit
Wazeer et al. (2025)	Plant waste extracts used in seed priming	Drought	Genotype-specific enhancement of maize drought tolerance

Photosynthesis, carbon assimilation, and biomass formation

A second key process is photosynthetic preservation. Both drought and salinity reduce gaseous exchange, chlorophyll activity, and carbon assimilation; thus, any intervention that normalizes photosynthetic activity has a potent impact on biomass growth and end result. Drought-induced humic acid regulated photosynthesis and enhanced the functional condition of the maize photosynthetic system (Chen et al., 2022). Salinity-stressed seaweed extract enhanced photosynthetic rate, internal CO2 concentration, and transpiration compared to untreated salt-stressed maize, indicating that physiological recovery caused by biostimulants can be directly associated with carbon economy (Pienaar et al., 2025).

These reactions are not simply descriptive. They are also coming to be linked with transcriptional and metabolomic reprogramming. Seaweed extract modified transcription of roots and leaves in maize under water deficit and caused changes in metabolites linked to stress adaptation, indicating that orchestrated control of metabolism, instead of a superficial greening impact, supports improved growth under stress (Tinte et al., 2022).

Antioxidant defense, osmolyte accumulation, and membrane protection

One similarity between drought- and salinity-damaged maize is oxidative stress. During these stresses, reactive oxygen species build up, membrane lipids are oxidized and enzyme systems like superoxide dismutase, catalase, peroxidase and ascorbate peroxidase are vital to the survival of the plant. Numerous contemporary maize research studies indicate that biostimulants reduce stress by enhancing the antioxidant defense and reducing oxidative markers. The same has been observed many times in case of seaweed extracts, humic substances, willow-based products, microbial inoculants, and chitosan-based treatments (Mutlu-Durak and Yildiz Kutman, 2021; Wu et al., 2024).

In harsh salinity conditions, native microbial and compost-based bio-stimulants enhanced maize dry weights, decreased hydrogen peroxide, and augmented peroxidase activity, suggesting that oxidative defense is among the key processes that explain growth recovery (Ouhaddou et al., 2023). Similarly, chitosan-fulvic acid nanoparticles boosted drought tolerance in maize by promoting antioxidant defense and transcriptional reprogramming, demonstrating how more recent formulations can enhance classical protective pathways by enhancing delivery and plant uptake (Brown et al., 2024).

Ion homeostasis, osmotic adjustment, and nutrient relations under salinity

In salty environments, it is essential to sustain positive K + / Na + proportions and mineral equilibrium to ensure survival of maize. Biostimulants can also be involved either directly, altering the behaviour of ion transport and membrane behaviour, or indirectly, by enhancing root health, rhizosphere processes and soil structure. This is especially evident with microbial and compost-related systems. Ouhaddou et al. (2023) found that local biostimulants enhanced soil structure and mineral composition, such as K and Mg, and had positive effects on plant fitness in salty conditions. Similar findings were demonstrated by D'Amato and Del Buono (2021), who demonstrated that the use of biostimulants alleviated the stress of salinity in maize, and the effect is caused by a co-existence of physiological and nutritional changes, rather than by a single characteristic.

The biostimulant action at salinity is thus best conceived as a multi-level buffering system: the osmotic disturbance is decreased, antioxidant defenses are strengthened, and ion/nutrient connections are separated to some extent. This also explains the increasing popularity of salinity oriented treatments that incorporate biologically active products along with rhizosphere-enhancing or soil-improving products instead of being reliant on such foliar stimulation (El-maghraby et al., 2024).

Table 3. Representative Recent Studies on Maize Biostimulants under Salinity Stress

Study	Biostimulant	Salinity context	Main maize response
Mutlu-Durak & Yildiz Kutman (2021)	Willow bark/leaf extracts	Early growth under salinity	Higher shoot fresh weight, root area, and lower oxidative damage
D'Amato & Del Buono (2021)	Biostimulant formulation	Salt stress	Mitigated growth suppression in maize plants
Li et al. (2021)	Bacillus sp. MGW9 seed biostimulant	Salt stress during germination	Improved maize salt tolerance at the germination stage
de Carvalho Neta et al. (2024)	Growth-promoting bacteria + AMF	Saline stress	Enhanced maize tolerance through microbial synergy
El-maghraby et al. (2024)	AMF + compost tea	Saline-sodic soil	Improved growth, microbial activity, and grain yield
Fan et al. (2024)	AMF	Sandy and saline–alkali soils	Yield increased by 25.77% in sandy soil and 18.63% in saline–alkali soil
Ouhaddou et al. (2023)	Compost, Bacillus, and AMF-based indigenous biostimulants	50–100 mM NaCl	Marked recovery of dry matter, antioxidant status, and soil quality under severe salinity
Pienaar et al. (2025)	Ecklonia maxima seaweed extract	Salt stress	Higher photosynthesis and improved morphological performance under salinity

Soil biological activation and rhizosphere engineering

Soil and rhizosphere activation is another important mechanism especially in the field agriculture. The microbial biostimulants can alter the structure and activity of the root-associated microbial communities, whereas non-microbial biostimulants could alter microbial activity by other means, altering the exudation patterns and soil carbon interactions. An example of this is that seaweed extracts disturbed the bacterial community structure of drought-stressed maize systems when spray drift was deposited on the soil, suggesting that some portion of their field effect is mediated by the rhizosphere instead of solely by leaf tissue reactions (Trivedi et al., 2022).

This mechanism has a high agronomic importance. A treatment that enhances root-soil contact can potentially give more stable responses during stress events than that that acts temporarily via foliage. This agrees with reviews that microbial-based products often enhance maize by enhancing nutrient capturing, microbial interaction, and soil activity, despite aboveground impacts differing with the season or level of stress (Ocwa et al., 2024).

Major Biostimulant Groups Used to Improve Maize under Drought and Salinity

The maize literature does not support the view that all biostimulant classes are equally mature. Instead, it shows a clear hierarchy of evidence. The strongest maize-specific evidence under drought and salinity is currently associated with microbial inoculants, humic/fulvic substances, and seaweed-based products. Amino acid, protein hydrolysate, willow- and plant-derived extracts, trehalose-type growth stimulants, and chitosan-based systems are scientifically promising, but they remain less consistently represented across multiple field environments (Ocwa et al., 2024).

Microbial Biostimulants

Microbial biostimulants are among the most scientifically convincing tools for maize stress mitigation because their effects extend beyond the plant to the soil-plant interface. In maize under salinity, Bacillus-based seed biostimulants improved germination-stage salt tolerance (Li et al., 2021), and combined bacterial-AMF systems enhanced overall stress tolerance in later growth stages (de Carvalho Neta et al., 2024). Under saline–sodic conditions, the combination of AMF and compost tea increased mycorrhizal

infection, microbial activity, growth parameters, and grain yield of maize, further confirming the usefulness of biologically integrated treatments (El-maghraby et al., 2024).

Field relevance is also evident. In sandy and saline–alkali soils, AMF application increased maize yield by 25.77% and 18.63%, respectively, while improving grain quality and soil nutrient availability (Fan et al., 2024). In severe salt stress, combinations involving Bacillus and compost generated very large relative gains in shoot and root dry matter in maize compared with untreated plants (Ouhaddou et al., 2023). These results indicate that microbial biostimulants are not merely laboratory curiosities but realistic components of resilient maize production systems.

Humic and Fulvic Substances

Humic and fulvic compounds continue to play key roles in maize biostimulant studies since repeatedly, they affect root development, nutrient uptake, osmolyte status, photosynthesis, and carbon metabolism. One of the most powerful studies of maize in the field was given by Chen et al. (2022), who demonstrated that humic acid during drought managed growth, photosynthesis, hormones, and osmolytes. Kaya et al. (2020) also established that sulfur-enriched leonardite and humic acid increased drought and phosphorus deficit tolerance in maize, indicating that humic-type products could help plants to cope with complex stress conditions instead of water deficit on its own.

The study of fulvic acid in nutrition-stress interactions in maize is also reinforced by recent studies. Fulvic acid improved low-nitrogen stress by facilitating root growth and nitrogen metabolism and increased maize yield and nitrogen efficiency of low-molecular-weight formulations (Li et al., 2024a; Li et al., 2024b). These studies are not necessarily carried out in the classical treatment of drought or salinity, but they are very useful since the nutrient acquisition and root vigor become determining under the stress-constrained conditions. Thus, humic and fulvic compounds must be considered as multifunctional biostimulants that help to strengthen maize resilience both physiologically and edaphically.

Seaweed and Microalgae-Derived Biostimulants

One of the most vibrant areas of present biostimulant studies is the use of seaweed extracts. Their usefulness in maize is in not only stimulating growth but also in a wide range of effects on antioxidant status, gene expression, and stress-responsive metabolism. Kappaphycus alvarezii extract was found to induce transcriptional modifications in maize roots during soil moisture stress in line with stress relief and enhanced performance under water stress (Kumar et al., 2020). Metabolomics also demonstrated that maize metabolism is reprogrammed by seaweed-derived formulations during drought, particularly pathways that are related to phenylpropanoid and antioxidant-related responses (Tinte et al., 2022).

Evidence of salt orientation is also promising. A commercial seaweed extract obtained using Ecklonia maxima enhanced morphology and photosynthetic activity of maize during salt stress and was linked to a metabolic re-programming of salt stress adaptation (Pienaar et al., 2025). Seaweed biostimulants Reviews also point out that their effects are frequently multi-layered, including hormone-like, antioxidant regulation, osmotic protection, and interaction with rhizosphere processes (Abdelkader et al., 2025).

The microalgae-based methods are also coming up. The potential of Chlamydomonas reinhardtii and Chlorella sorokiniana as biostimulants in maize suggests that algal products could offer another pathway to growth stimulation and stress buffering that is environmentally friendly (Martini et al., 2021). Nevertheless, the maize proof base of microalgae is smaller than that of seaweed extracts.

Amino Acid, Protein Hydrolysate, and Related Organic Stimulants

Current literature is highly active in discussing amino acid and protein hydrolysate biostimulants due to their potential of moderating nitrogen metabolism, enzyme activities, osmotic regulation, and stress signaling. In general, their scientific foundation has been reviewed well in recent articles (Sun et al., 2024). However, the direct evidence of maize under drought and salinity is not as widespread as microbial or

seaweed products. This is not to say there is poor potential but it just means that there is less maize-specific data pool under specified stress conditions.

There are some field and greenhouse studies, however, which promise. Abdo et al. (2022) indicated that growth stimulants such as humic, amino-related components could be used to stimulate the growth of maize and reduce the dependence on chemical fertilizers. Li et al. (2022a) discovered that trehalose was more effective than chitosan, humic acid, and gamma-aminobutyric acid at promoting the growth of field maize, which demonstrates that organic biostimulants may be compared to each other and may show acute differences even within seemingly similar categories. In terms of review, this highlights a key point, which is that amino acid/protein-derived products cannot be lumped together, as their efficacy is highly dependent on composition, concentration, and physiological target.

Chitosan and Nano-Enabled Biostimulants

Biostimulants based on chitosan are gaining increasing interest in maize due to their combination of elicitor-like action and the potential to be delivered better when incorporated into nano-formulations or coating. In sweet corn, seed performance under drought was enhanced by chitosan- and mineral-based coatings (Behboud et al., 2024). In maize seedlings, O-carboxymethyl chitosan nanoparticles improved water stress tolerance, whereas chitosan-fulvic acid nanoparticles enhanced drought tolerance through antioxidant defense and transcriptional reprogramming (Brown et al., 2024).

Scientifically, these findings are highly relevant because they show how formulation technology can alter the mode and intensity of plant response. However, the literature is still developing, and field-scale confirmation is less abundant than for humic or microbial biostimulants. Therefore, chitosan and nano-enabled approaches should currently be interpreted as advanced, promising, but still less fully validated maize biostimulant strategies.

Agronomic Consequences for Growth and Yield of Maize

From an agronomic standpoint, the principal question is not whether biostimulants can change maize physiology, but whether they can do so consistently enough to protect growth and yield under real stress conditions. The available evidence suggests that they often can, but not automatically. In the systematic maize review by Ocwa et al. (2024), biostimulants generally improved grain yield more distinctly than grain quality, while integrated applications often outperformed single products. This is an important practical conclusion because it suggests that the best agronomic role of biostimulants may be as part of a stress-management package rather than a stand-alone intervention.

Application timing and method are decisive. Seed treatment is particularly useful for enhancing emergence and early establishment under stress, as seen with Bacillus inoculants and willow-derived products under salinity (Mutlu-Durak & Yildiz Kutman, 2021). Application or inoculation of soils is particularly useful in cases where root growth, mycorrhization, and soil functioning are strategically targeted. Foliar application can be useful to achieve rapid physiological modulation, particularly in systems based on seaweeds, but it can be more sensitive to environmental timing and canopy capture (Kumar et al., 2020; Pienaar et al., 2025).

Another agronomic consideration is yield stability. There are studies that have shown very large relative improvements at very severe stress levels, since the untreated control is very stressed; in other studies there is smaller but still useful improvement at moderate stress levels. Thus, the usefulness of biostimulants is not only a percentage increment, but also a measure of their capacity to stabilize maize performance in season, soil, and stress levels. In this regard, products which also enhance the rhizosphere functionality, root growth, and physiological tolerance are expected to deliver the most sustainable benefit in the field (Liaqat et al., 2025).

Limitations, Research Gaps, and Future Perspectives

Although the literature has grown greatly, there are still a number of limitations that do not allow the complete agronomic normalization of biostimulants in maize. To begin with, there is an endemic issue of product heterogeneity. The bioactive composition, extraction method, microbial viability, or carrier system of the products sold under the same category may be vastly different. Second, controlled conditions are used in many experiments and in the fields of farmers, stress is dynamic, heterogeneous and often coupled with nutrient or temperature constraints. Third, there is a lack of consistency in the reporting of dose, timing, and product composition across studies, which makes it difficult to compare results of meta-comparisons or build recommendations (Ocwa et al., 2024).

Another scientific gap is related to integrated stress situations. Drought and salinity tend to go together in irrigation-based systems and marginal lands but numerous maize experiments have only isolated a single stress. It is also necessary to conduct more explicit genotype-by-biostimulant interaction studies since maize hybrids vary in root architecture, transpiration behavior, ion tolerance and reproductive sensitivity. A treatment that is effective in a given hybrid or stress phase might not be the same in another (Liaqat et al., 2025).

Future studies are thus recommended to proceed in four directions: (1) multi-location field experiments under natural drought and salinity gradients; (2) more product characterization through chemistry or microbial composition to plant response; (3) synthesizing omics-level evidence with agronomic phenotyping; and (4) the establishment of crop- and stress-specific decision space instead of generic promotional assertion. The most promising next-generation approach in maize is probably not a single, miracle product, but well-crafted mixtures of microbial and non-microbial biostimulants, depending on the type of stress, the state of the soil, and the developmental stage of the crop (Abdelkader et al., 2025).

Table 4. Major Limitations and Future Research Priorities for Biostimulant Use in Maize under Drought and Salinity

Issue	Why it matters for maize biostimulant research	Priority recommendation
Product heterogeneity	Products within the same class may differ strongly in active composition or microbial viability	Require detailed product characterization and reporting
Single-stress bias	Most maize studies test drought or salinity separately, although both often co-occur	Expand research to combined drought–salinity scenarios
Field inconsistency	Responses vary with hybrid, soil type, season, and stress severity	Increase multi-location and multi-season validation
Mechanistic overgeneralization	Positive outcomes are sometimes reported without linking them to measurable mechanisms	Integrate physiology, metabolomics, transcriptomics, and yield data
Application strategy uncertainty	Dose, timing, and route of application strongly affect outcomes	Develop crop-stage-specific protocols for maize
Genotype specificity	Different maize hybrids differ in root traits and stress sensitivity	Test genotype × biostimulant interactions explicitly

Conclusion

The existing body of scientific knowledge confirms that the biostimulants have a great potential to enhance maize growth and yield in the conditions of drought and salinity, although their efficiency is dependent on the classes and context. The most consistent and logical maize-specific support is currently provided by microbial inoculants, humic/fulvic compounds and seaweed-based products. These advantages are mediated by root reinforcement, enhanced water relations, photosynthetic protection, antioxidant activation, osmotic adjustment, and at low salinity, enhanced ion and rhizosphere regulation.

Meanwhile, scientific rigor demands a moderate understanding. Biostimulants are not to be promoted as a universal substitute of good agronomic management. They are most beneficial when there is a close alignment between product choice, stress diagnosis, the time of application, and soil-crop context. Thus, they can expect to play a physiologically smart complement to fertilizer, water and soil-management techniques in their future role in maize production, particularly in systems that are becoming more vulnerable to drought and salinity. Biostimulants will be a key pillar of resilient and sustainable maize production with enhanced standardization and field validation that revolves around maize.

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Conflict of Interests

No conflict of interest.

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