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Biostimulants: An overview and role in sustainable wheat production

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Abstract

Wheat (*Triticum aestivum* L.) is extensively cultivated across the globe and serves as an essential crop for sustaining food systems and nutritional security, with pronounced importance in developing countries. However, intensive reliance on chemical fertilizers to sustain high wheat productivity has led to soil degradation, environmental pollution, and declining nutrient use efficiency. In the scenario of climate change and increasing biotic stress and abiotic stress, there is an need of immediate attention for sustainable alternatives that can enhance crop performance while preserving soil health. Biostimulants have emerged as promising tools in sustainable wheat production due to their potential to improve plant physiological processes, nutrient uptake efficiency (NUE), grain quality, yield and stress tolerance when applied in small quantities. This review synthesizes current knowledge on the types of biostimulants, including microbial (rhizobacteria, *Trichoderma* spp. and *Arbuscular mycorrhizal fungi*) and the non-microbial sources (seaweed extracts, humic products and protein hydrolysates substances) and their mechanisms of action in wheat. Evidence from recent studies demonstrates that biostimulants positively influence wheat growth, yield attributes, photosynthetic efficiency, root architecture, soil nutrient availability and microbial activity, while enabling partial replacement of chemical fertilizers under integrated nutrient management systems. The review highlights the role of biostimulants in improving wheat productivity, soil quality, and resilience to environmental stresses, thereby supporting sustainable and climate-smart agricultural practices. Continued research, standardization, and field-level validation are essential to fully exploit their potential in large-scale wheat cultivation.

Keywords: Wheat, biostimulants, sustainable, humic acid, seaweed extract

Introduction

Cereals are essential for meeting the world's expanding population's food needs, especially in poor countries where the sole major source of calories and nutrition is a cereal-based production system (Nikos and Jelle, 2012; Shiferaw *et al.*, 2013) ^[71]. The nutrient-rich cereal is cultivated in various environmental conditions; globally, wheat covers approximately 217 million hectares, making it the crop with the largest acreage, with production of about 731 million tones, annually. (USDA, 2019).

The "king of cereal," wheat (*Triticum aestivum* L.), is a significant staple food cereal crop that has been cultivated since ancient times and belongs to Poaceae family. For most people on the entire globe, it is the first significant and strategic cereal crop. With approximately 13% protein, 1.8% fat, and 59.2% starch, as well as vital elements including manganese, phosphorus, niacin, and B vitamins, wheat is a nutritionally complete dietary source (Khedkar *et al.*, 2025) ^[45]. According to Sharma and Sendhil (2019), ^[68] Wheat has been available worldwide since ancient times and used in a variety of processed forms like *chapatti*, *halwa* and other baked goods. Wheat has a substantial socioeconomic impact and is a staple food for both people and animals due to its high potential for yield per unit area and ability to thrive in practically every agroclimatic condition. With a 36% share of the total food grains produced in India, wheat contributes significantly to the consumption of food baskets and guarantees both food and nutrition security. The government purchases wheat in large quantities and distributes it to the majority of the population. Since ancient times, wheat has been consumed in a variety of processed forms and is available throughout the nation as one of the least expensive sources of

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energy (Sharma and Sendhil, 2019) ^[68]. India is another largest producer of wheat in globe, due to its diverse agroecological conditions, which have ensured food and nutrition security for the majority of its population through production and a sustained continuous supply, especially in recent years (Sharma and Sendhil, 2015; Sharma *et al.*, 2015) ^[69, 70].

Both, Improving yield and crop quality due to the world's expanding population while preventing losses from living and nonliving factors, which are currently 30-40% and 60-70%, respectively, and minimizing the environmental and health effects of the extensive use of fertilizers and chemical products meant to enhance crop quality and yields are current two issues in current cultivation practices and upcoming perspectives for agriculture based industries (Colla *et al.*, 2017; Win *et al.*, 2018) ^[22, 78]. Furthermore, as the world's population increases and the demand for foods with higher nutritional value and health values develops, there is growing demand to produce enough food. On the other side, the soils are gradually losing essential nutrients needed for crop growth, which lowers crop yields per unit of land. Keeping in mind that, chemical fertilizers can boost crop growth and yields when used properly, but excessive use can lead to a number of negative impacts, including declining soil fertility, hardening the soil, making pesticides more effective, and contaminating water. Additionally, these chemicals have a critical role in maintaining plant health and alter the composition of the soil microbiome, which increases plant susceptibility to diseases. In the long run, this poses a serious risk to consumers and the ecosystem as a whole. As a result, contemporary farming methods are looking for substitutes for artificial fertilizers. Organic, alternative, and low-input sustainable agriculture must replace chemical-based conventional farming methods in order to mitigate the ill effects of excessive agrochemical use on people and the environment and to satisfy resource poor farmers' demands for fertilizer (Bhatia, 2002) ^[13].

As fertilization is crucial to increasing crop output, farmers typically use large amounts of chemical fertilizers during wheat production in order to harvest large grain yields. The excessive use of chemical fertilizers in agricultural farming, however, has detrimental effects on the environment, such as deteriorating soil fertility, absorbing organic matter, reducing the amount of water that may remain held, and causing nutrient mobilization and uptake by the root zone (Xiao *et al.*, 2019) ^[79].

There is a recent trend toward reducing the usage of chemically synthesized fertilizers and adopting bio-organic farming technology, commonly referred to as sustainable agriculture, because of the detrimental consequences on the health of human being and environment. Utilizing organic matter and advantageous microorganisms, bio-organic farming produces high-quality, nutritious food in a sustainable manner (Mallik and Williams, 2008) ^[53].

Farmers adopting advanced integrated nutrient management (INM) practices can significantly reduce the use of chemically synthesized fertilizers, thereby minimizing adverse impacts on human health and the environment (Chauhan *et al.*, 2024), ^[19] which highlights the growing importance of biostimulants in modern agriculture. Biostimulants are naturally derived organic substances, microorganisms, or their combinations that enhance plant growth and performance under diverse environmental conditions (Rouphael and Colla, 2020; Bhupenchandra *et al.*, 2020) ^[15, 62]. As defined under the Fertilizer (Control) Amendment Order, 2021 of the Indian government, biostimulants primarily stimulate plant physiological processes, improve nutrient uptake efficiency, and enhance crop growth, yield, quality, and tolerance to stress conditions, a concept that

aligns with the definition of the European Biostimulants Industry Council, which emphasizes improved nutrient use efficiency and the abiotic stress tolerance (EBIC, 2016) ^[28]. Biostimulants include a wide range of products such as amino acids, hydrolysates of protein botanical extracts including seaweed extracts, vitamins, anti-transpirants, microbial metabolites, antioxidants, humic and fulvic acids, and a range of related derivative compounds (Khurana and Kumar, 2022) ^[46]. Unlike fertilizers and the organic manures, they are applied in small quantities (du Jardin, 2015) ^[27] and contribute to maintaining agroecosystem balance by reducing dependence on synthetic fertilizers, pesticides, and heavy metal inputs. Recognizing their ability, the European Commission (EU) has set a target to replace about thirty percent of chemical fertilizers with organic and sustainable alternatives by end of 2050 (Hansen, 2018) ^[39]. With increasing concerns over sustainable ecosystems and global food security, the adoption of biostimulants is rapidly expanding, and Li *et al.* (2022) ^[50] reported that their application in cereals, legumes, fruits, and vegetables resulted in an average yield increase of 17.9 percent, demonstrating their broad agronomic benefits.

Biostimulants: Types and their influence

Crop production is increasingly constrained by multiple abiotic (environmental) and biotic (biological) stress factors, which can cause losses of produce up to 50 percent at the global level (Sangiorgio *et al.*, 2020) ^[65]. Biostimulants are organic inputs applied to plants to enhance quality attributes, nutrient use efficiency, and tolerance to abiotic stresses, independent of their nutrient composition (du Jardin, 2015) ^[27]. Consequently, the use of biostimulants is considered a sustainable strategy for improving food security, as they strengthen plant resilience to stresses associated with climate change (Yakhin *et al.*, 2017) ^[81]. Biofertilizers, in contrast, are eco-friendly inputs containing beneficial microorganisms viz., bacteria, fungi, or microalgae that are said to promote plant growth by colonizing the rhizosphere and facilitating improved uptake of essential nutrients like N,P,K and other minerals (Win *et al.*, 2018; Bhattacharjee and Dey, 2014) ^[14, 78]. Biostimulants, however, are substances that, when applied in small quantities, they enhance plant physiological processes, leading to improved nutrition, stress tolerance, yield, and quality without negatively affecting the surrounding ecological system (Barone *et al.*, 2018; Kopta *et al.*, 2018) ^[9, 48]. Based on their origin, biostimulants are broadly classified into microbial biostimulants, including plant growth-promoting rhizobacteria, *Trichoderma* spp., and arbuscular mycorrhizal fungi (AMF) (Colla and Rouphael, 2015), ^[21, 23] and non-microbial biostimulants such as humic and fulvic acids, seaweed extracts, protein hydrolysates, and related compounds. Owing to their high solubility and ability to proliferate in the rhizosphere, the both kind of biostimulants have strong potential to mitigate yield limitations imposed by environmental stresses in field and horticultural crops, while reducing reliance on chemical fertilizers and other agrochemicals. Biostimulants can be applied through foliar spray, fertigation, or direct soil application to promote crop growth, development, and quality (Van Oosten *et al.*, 2017) ^[76]. Recently, Lau *et al.* (2022) ^[49] emphasized the practical use of biostimulant formulations, noting their effectiveness when applied directly to soil, alone or in combination with micronutrients, as well as their application in seed priming to enhance synergistic plant growth. Overall, biostimulants represent a sustainable approach to minimizing environmental risks by reducing the negative impacts associated with excessive and indiscriminate use of chemical inputs.

(A) Microbial biostimulants

The use of microbial inoculants in agriculture has expanded considerably over the past two decades (Hayat *et al.*, 2010),^[40] driven by the need to address the challenges of modern farming through both public and private research initiatives. Microbial inoculants have proven that they enhance the uptake of nutrients both macro and trace, although the exact working mechanisms are still being elucidated. Improvements in nutrient use efficiency, root biomass, and root hair development may indirectly facilitate better nutrient absorption. Various microorganisms, including *Bacillus spp.*, *Acinetobacter sp.*, *Azospirillum spp.*, *Pseudomonas sp.*, and arbuscular mycorrhizal fungi (AMF), have been reported to enhance the uptake of sulfur (Banerjee *et al.*, 2006),^[8] zinc (Kohler *et al.*, 2008; Yazdani and Pirdashti, 2011),^[47, 82] calcium (Giri and Mukerji, 2004 and magnesium^[34] (Khan, 2005),^[44] and copper and manganese (Liu *et al.*, 2000)^[51]. These microbial inoculants function as biofertilizers and are also classified as microbial biostimulants in this context. Microbial biostimulants (MBSts), particularly plant growth-promoting rhizobacteria (PGPR), support crop development by acting as natural growth enhancers in the rhizosphere (del Carmen Orozco Mosqueda *et al.*, 2020)^[26]. They facilitate nutrient acquisition through processes such as phosphate solubilization, nitrogen fixation, siderophore production, and disease suppression, and they participate in signaling pathways via secondary metabolites, polysaccharides, antibiotics, amino acids, and phytohormones (Gupta *et al.*, 2021)^[38]. In addition to non-microbial biostimulants, the microbial biostimulants like PGPR and AMF are recognized as sustainable tools for maintaining yield stability under low-input conditions, especially under nitrogen and phosphorus deficiencies, while also enhancing crop tolerance to abiotic stresses such as drought condition, salinity, and extreme temperatures range (Rouphael and Colla, 2020)^[62]. Dal Cortivo *et al.* (2020)^[24] demonstrated that direct seed application of biofertilizers can promote sustainable wheat production without disturbing the native soil microbiome. Furthermore, Achari *et al.* (2021)^[1] reported that applying *Azotobacter* and *Azospirillum* along with 140 kg/ha nitrogen significantly improved wheat growth parameters and overall grain and straw yield.

(B) Non microbial biostimulants

Protein hydrolysates (PHs)

Protein hydrolysates (PHs) are biostimulants abundant in signaling peptides and free amino acids, and they are widely employed to enhance seed germination, seedling growth, overall plant development, crop yield, and the quality, particularly under stress conditions (Colla *et al.*, 2017)^[22]. These protein based hydrolysates biostimulants can be delivered via seed priming, soil drenching, or foliar spraying (Agliassa *et al.*, 2021)^[2]. PHs enhance plant stress tolerance by stimulating defense mechanisms and promote growth under optimal conditions by improving leaf gas exchange, photosynthetic pigment content, water-use efficiency, and root system architecture through increased length of roots, branching, and surface area (Rakkammal *et al.*, 2023; El-Nakhel *et al.*, 2021)^[29, 58]. Moreover, they exhibit hormone like activities that regulate carbon and nitrogen metabolism and strengthen antioxidant capacity, thereby supporting overall plant growth and development (Colla *et al.*, 2015; Caruso *et al.*, 2019)^[18, 21, 23].

Seaweed extracts

Seaweed extracts (SWEs) are important organic non-microbial biostimulants, commonly derived from red, green, and brown

macroalgae for use in agricultural and horticultural crops (Rouphael and Colla, 2020)^[62]. Market available SWEs are predominantly derived from red seaweeds such as *Gracilaria edulis*, *Acanthoporphyrus spicifera*, and *Gelidium robustum*, and brown seaweeds including *Ascophyllum nodosum*, *Laminaria setchellii*, *Sargassum hildebrandtii*, *Macrocystis pyrifera*, *Sargassum horridum*, and *Ecklonia arborea* (Singh *et al.*, 2018; Ali *et al.*, 2021)^[4, 73]. Polysaccharides, which constitute approximately 30-40% of these extracts, are their primary components (Battacharyya *et al.*, 2015). SWEs possess a composite mixture of multiple components like polysaccharides, micronutrients, and plant hormones that stimulate plant growth and improve tolerance to both abiotic and biotic stresses (González *et al.*, 2013)^[35]. Additionally, they enhance soil physico-chemical properties by increasing nutrient availability, promoting beneficial microbial populations, and improving soil water retention. Secondary metabolites present in SWEs also participate in plant signal transduction, enabling plants to respond to nutrient deficiencies and stress conditions such as drought by activating stress-responsive pathways (Shukla *et al.*, 2018)^[72]. Research indicates that the application of SWEs in sustainable agriculture promotes soil health, supports beneficial microorganisms, enhances nutrient uptake, and ultimately improves plant growth and resilience to stress (Ali *et al.*, 2021; Xu and Geelen, 2018)^[4, 80].

Humic substances

Humic substances (HSs), formed through microbial decomposition and chemical breakdown of organic matter in soil, play vital roles in soil and plant processes (Schiavon *et al.*, 2010; Berbara and García, 2013)^[12, 67]. They are generally classified as fulvic acids, which are soluble in both acidic and alkaline conditions; humic acids, soluble in basic solutions but precipitated in acidic conditions; and humins, which are insoluble (Calvo *et al.*, 2014)^[16]. HSs are obtained from diverse sources such as vermicompost, earthworm casts, low-rank coals (peat, lignite, leonardite), and soil using various extraction methods, with recovery efficiency depending on the source and technique employed (Fatima *et al.*, 2021)^[30]. Structurally, they are heterogeneous brown to dark brown mixtures of polypeptides, fatty acids, sugars, and aliphatic and aromatic compounds interacting through hydrophobic forces (Guo *et al.*, 2019)^[37]. Widely used as biostimulants, HSs enhance plant growth and help plants tolerate biotic and abiotic stresses by improving soil physicochemical properties and regulating plant physiology (Huculak-Maczka *et al.*, 2018). They modulate various physiological processes during vegetative and reproductive stages by affecting functional proteins involved in energy metabolism, and protein synthesis (Canellas *et al.*, 2015; Roomi *et al.*, 2018),^[17, 61] while also upregulating genes associated with nutrient uptake, metabolism, and photosynthesis, thereby influencing key primary metabolic processes in plants (Trevisan *et al.*, 2011)^[74].

Biostimulants-a sustainable wheat production approach

Governments worldwide are increasingly promoting the usage of biostimulants to enhance food and nutritional security, encourage farming practices organically, and foster sustainable agricultural and cultivation practices, which has stimulated the development of innovative products (Arnau and Richard, 2016; Garcia-Gonzalez and Sommerfeld, 2016)^[6, 32]. Biostimulants provide a sustainable means of improving crop performance while enhancing soil health through the stimulation of beneficial microbial interactions. They positively influence plant

physiology and biochemistry by increasing photosynthetic pigments (chlorophyll and carotenoids), enhancing antioxidant activity, promoting root growth, improving nutrient use efficiency (NUE), and reducing dependency on chemical fertilizers (Malik *et al.*, 2020) [52]. Biobased biostimulants complement conventional agrochemicals, supporting nutrient uptake and stabilizing yields under both optimal and stressful conditions (Fiorentino *et al.*, 2018; Rouphael *et al.*, 2018) [31, 63]. Both microbial and non-microbial biostimulants also improve plant tolerance to both living and non-living stress factors while contributing to overall soil health and crop productivity.

Effect of biostimulants on plant growth, yield, and yield attributes

Popko *et al.* (2018) [57] evaluated amino acid-based plant growth stimulants, AminoHort and AminoPrim, on winter wheat and reported increased grain yield, improved quality traits, and higher macro- and micronutrient content. AminoPrim at 1.0 L ha⁻¹ increased grain yield by 5.4%, while AminoHort at 1.25 L ha⁻¹ improved yield by 11%. Mohan *et al.* (2024) [54] reported that foliar application of Hairamin with 75% RDF increased grain yield (47.29 q ha⁻¹) and biological yield (109.45 q ha⁻¹), showing that 25% of chemical fertilizers can be substituted with biostimulants rich in organic carbon, nitrogen, calcium, and amino acids, while supporting soil health.

Rathor *et al.* (2024) [59] observed that humic acids (HA) enhanced wheat shoot and root growth by stimulating auxin and cytokinin biosynthesis, improving root hair proliferation, biomass, and nutrient and water uptake. Sallume *et al.* (2023) [64] summarized that foliar application of HA at 1.5 g L⁻¹ combined with zinc nanoparticles (60 mg L⁻¹) maximized improvements in wheat morphological traits, yield, and seed zinc content. Choudhary *et al.* (2023) [20] showed that seed treatment with seaweed extract (3 mL kg⁻¹) significantly increased plant height, ear length, grains/ear, test weight, and grain yield (3109 kg ha⁻¹). Jodaugiene *et al.* (2023) found that fertilizers containing humic acids and silicon enhanced photosynthetic capacity in spring wheat, increasing chlorophyll a, b, and total pigments at flowering and milk maturity stages, along with aboveground and root biomass, leaf area, and grain quality. Rohulla *et al.* (2023) [60] concluded that use of seaweed extract as foliar at 4 mL L⁻¹ during tillering and heading stages increased leaf area index and dry matter accumulation 30 days after sowing, while 2 mL L⁻¹ showed no significant effect. Behl *et al.* (2024) [11] found that foliar application of Hairamine protein hydrolysate improved plant height, chlorophyll content, stem strength, and grain yield traits across three wheat varieties (DBW 222, WH 1270, DBW 303). Sarita *et al.* (2021) [66] demonstrated that foliar application of seaweed extract at 4 mL L⁻¹ during tillering and heading stages enhanced wheat biological, grain, and straw yield, comparable to 2 mL L⁻¹. Achari *et al.* (2021) [1] reported that combining *Azotobacter* and *Azospirillum* with 140 kg ha⁻¹ N significantly improved wheat growth, tillering, spike length, test weight, grains per spike, and overall yield. Kaur *et al.* (2024) [43] concluded that integrating Hairamine with reduced chemical fertilizers (50% RDF + 25% vermicompost + three foliar sprays) maintained high grain yield, plant height, tiller number, and dry matter accumulation, supporting sustainable wheat production.

Effect of biostimulants on soil nutrient uptake, soil nutrient status, and soil properties

Amaral and Brown (2022) [5] suggested that foliar application of myo-inositol combined with zinc enhances zinc mobility and accumulation in grains without negatively affecting other

essential metals or yield. Mohanta *et al.* (2020) [55] reported that total nutrient uptake was highest with 125% RDF + *Azotobacter* + phosphate-solubilizing microorganisms and lowest in the control. Ajeng *et al.* (2020) [3] found that seedlings grown in utisol with 70% chemical fertilizer + 30% biofertilizer (actinomycetes) had maximum NPK uptake, exceeding that in oxisol, histosol, and spondosol by 14%, 20%, and 38%, respectively. Deepa *et al.* (2019) [25] observed that inoculation with *Azotobacter* improved growth parameters, enhanced soil microbial activity, promoted nitrogen fixation, and increased wheat yield. Aziz *et al.* (2024) [7] reported that combining biochar (20 t ha⁻¹) with chemical fertilizers improved soil nutrient status, soil organic carbon, and microbial biomass, increasing populations of actinomycetes (24%), bacteria (70%), AMF (49%), and saprophytic fungi (38%). This treatment also enhanced wheat growth and yield traits along with higher soil enzyme activities such as dehydrogenase (44%) and β -glucosidase (93%). Principal component analysis confirmed that allied application of biochar with chemical fertilizers is highly effective for improving soil fertility, microbial activity, and hence crop productivity.

Conclusion

Bio-stimulants are an exciting and integral part of the future of sustainable agriculture. They offer a variety of benefits, including better resilience towards environmental stresses, reduced dependency on chemical fertilizers and pesticides and improved crop yields. By improving soil health, improving nutrient and water use efficiency (WUE), and stimulate growth of plant, biostimulants can play a significant role in environmental sustainability and ensuring food security. However, challenges such as regulatory gaps, field variability, and cost concerns must be addressed to maximize the potential of bio-stimulants. Continued research and development, along with targeted education for farmers, will help unlock the full benefits of these innovative products, making them a cornerstone of sustainable agricultural practices worldwide.

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