

Role of Biostimulants in Wheat: Nutritional Quality and Resistance to Abiotic Stresses, a Systematic Review

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Abstract

Wheat is a major staple crop, and improving its productivity and grain quality is essential to meet rising global food demand. Biostimulants have attracted growing interest because they can enhance nutrient use efficiency, improve tolerance to environmental stresses, and support crop performance without acting as conventional fertilizers, yet a focused synthesis of their effects on wheat remains limited. Following a systematic search of Scopus and Web of Science (2000–2026), this review synthesizes 52 primary studies on microbial and non-microbial biostimulants in common and durum wheat, addressing grain yield, nutritional quality, and resilience to drought, salinity, heavy metals, and temperature extremes. Across studies, 88% reported significant positive effects and none reported a consistent negative effect; grain yield increases ranged from +6% to +123%, with parallel improvements in grain protein and micronutrient biofortification, notably zinc and iron. Microbial biostimulants, especially bacteria and microbial consortia, produced the largest but most variable gains, whereas non-microbial products gave more moderate and consistent responses. Benefits were greatest under low nitrogen, drought, and saline conditions and in nutrient-poor soils, and were modulated by wheat genotype and product dose. Biostimulants are promising tools for sustainable wheat production, though standardized field trials and reporting are still needed.

Keywords: climate change; sustainability; food security; food safety; biostimulants; abiotic stresses



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1. Introduction

Wheat stands as one of the most widely cultivated and consumed grains globally, providing essential dietary calories, proteins, vitamins, and minerals to approximately 20% of the world's population. This versatile cereal also contains valuable bioactive compounds like fiber, polyphenols, and carotenoids, contributing to its nutritional value. Global wheat production reached 798 million tons in 2024 [1]. Common wheat (*Triticum aestivum* L.) makes up the bulk of this production, representing around 95%, with durum wheat (*Triticum durum* Desf.) accounting for the remaining 5% [2–6]. One of the key reasons why wheat is considered a crucial staple crop is its versatile nature, being the primary ingredient in a wide variety of products like bread, noodles, couscous, and pasta [7]. In Italy, wheat

plays a significant role in the national cereal market, making a substantial contribution to the European Union's economy [7,8]. It covers an expansive area of 1.7 million ha and yielded total production of 7.3 million tons in 2021, accounting for 3% of Europe's wheat output that year [1]. The Food and Agriculture Organization (FAO) projects a global population of 9.1 billion by 2050, leading to a projected 70% increase in demand for major grain crops like wheat [9]. To meet these growing needs, wheat yields must increase by 1.6% annually [10,11]. Recent decades have seen agronomic practices focused on enhancing crop productivity through intensive fertilizer and chemical use, often overlooking the socio-economic and ecological impacts [12–14].

There is now a pressing need to explore safer, sustainable fertilization methods to enhance agroecosystem sustainability while maintaining competitive crop yields [15]. Utilizing environmentally friendly technologies can help reduce negative impacts like ecosystem degradation and high greenhouse gas emissions [16]. One promising approach to mitigate the environmental consequences of chemical fertilizers is the application of biostimulants.

In accordance with the European Regulation on fertilizers (2019/1009) ratified by the European Parliament, a plant biostimulant (PB) is defined as a product that enhances key plant nutrition processes without directly supplying nutrients. The main purpose is to improve specific characteristics of the plant or the plant rhizosphere, such as nutrient use efficiency, tolerance to environmental stress, quality traits, or the availability of essential nutrients in the soil or rhizosphere. Plant biostimulants are generally grouped into two categories: non-microbial and microbial PBs. Non-microbial PBs include a variety of substances like chitosan, humic acids (HA) and fulvic acids (FA), protein hydrolysates, organic materials (sewage sludge extracts, composts, and manure), phosphates, seaweed extracts (SE), beneficial elements (Al, Co, Na, Se, and Si), antitranspirants (kaolin and polyacrylamide), amino acids (AA) and N-containing compounds (peptides, polyamines, and betaines), and plant extract-based PBs [17–19]. On the other hand, microbial PBs consist of arbuscular mycorrhizal fungi (AMF), plant growth-promoting rhizobacteria (PGPR), and *Trichoderma* spp. [20–22].

However, despite their promising agronomic effects, the formulation and application of biostimulants are inherently complex. Their heterogeneous composition, variability of raw materials, and lack of single active ingredients make standardization difficult. In addition, their performance is strongly influenced by environmental conditions, soil properties, crop genotype, and management practices, resulting in highly variable field responses [17,18]. This variability also complicates dosage optimization and limits reproducibility of results across different agroecosystems.

Nevertheless, certain biostimulant sources such as microalgae cultivated in controlled systems (e.g., closed photobioreactors) offer a notable advantage in terms of compositional consistency. Unlike open cultivation systems, photobioreactors allow precise control over environmental and operational parameters (e.g., light, temperature, nutrients, and CO₂ supply), reducing contamination risks and enabling more reproducible biomass production with more stable biochemical profiles [23,24]. This higher level of process control facilitates standardization and may improve the reliability and scalability of microalgae-based biostimulant formulations.

From a safety perspective, biostimulants are generally considered low risk compared to conventional agrochemicals, particularly when derived from natural or microbial sources. However, wheat is a major food and feed crop, and large-scale or repeated applications require careful consideration of potential indirect effects. These include possible long-term changes in soil microbial communities and uncertainty regarding cumulative ecological impacts under intensive use scenarios [25].

In general, biostimulants are not considered harmful to human or animal health when properly formulated and applied, also because they must comply with the requirements of the EU Fertilizing Products Regulation (EU) 2019/1009, which establishes strict criteria for safety, quality, and labeling of products placed on the market. Nevertheless, although no evidence currently indicates direct risks to human or animal health under these regulatory frameworks, further long-term assessments are required to fully evaluate environmental persistence and indirect food-chain implications.

They can be applied either through foliar spraying or soil application and may come in hydrolyzed, fermented, or extracted forms. Biostimulants are generally considered environmentally friendly compared to conventional agrochemicals; however, their environmental safety may vary depending on their composition, origin, and application rate. In this context, they have been proposed as tools to support more sustainable agricultural systems by potentially reducing soil degradation and environmental pollution [26]. It should be noted that plant growth regulation in agriculture historically included both natural and synthetic compounds, which are now clearly distinguished from biostimulants under current European regulatory frameworks. Biostimulants can be used on wheat with several beneficial effects (Figure 1).

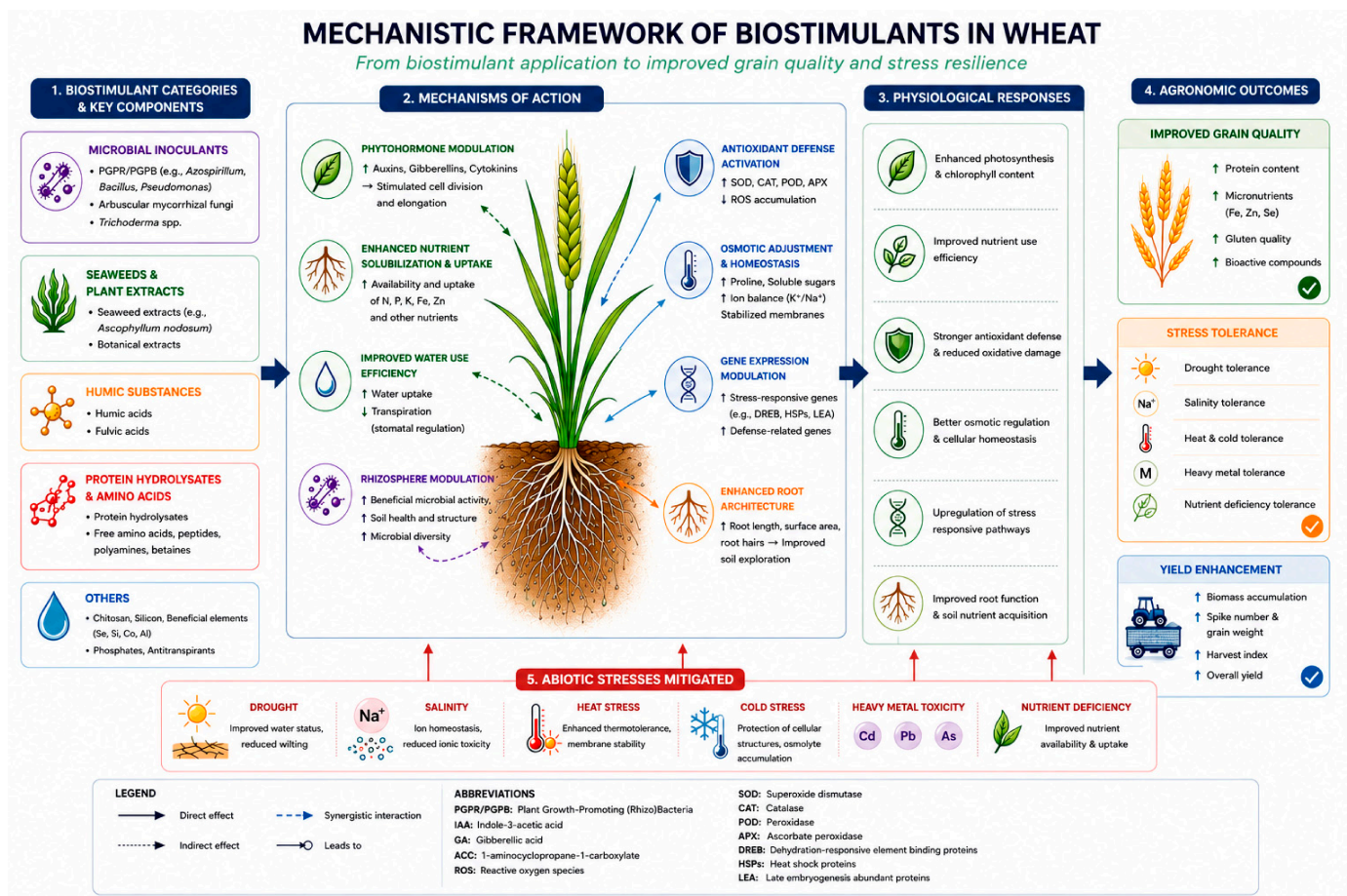


Figure 1. Mechanistic framework of biostimulant action in wheat. Biostimulants enhance nutrient and water uptake, antioxidant defense, stress-responsive pathways, root development, grain quality, yield, and tolerance to abiotic stresses. The figure was generated with the assistance of an artificial intelligence tool and reviewed by the authors for scientific accuracy.

The market for biostimulant products has shown significant growth in recent years. In 2015, the biostimulant market in Europe was valued at approximately 500 million euros, representing nearly 30% of the global market share [27]. Projections by analysts suggest

that by 2025, the global biostimulant market will exceed four billion dollars [28]. This remarkable growth can be attributed to the increasing demand for biostimulants that provide more effective action in promoting plant growth and resilience to abiotic stress. There is also greater emphasis on optimizing the use of agrochemical inputs and reducing the environmental impact of agricultural production systems [29].

In response to this growing market, the European regulatory framework has been strengthened through Regulation (EU) 2019/1009, which harmonizes requirements for fertilizing products, including biostimulants, across the EU. This regulation establishes criteria for safety, labeling, and conformity assessment, supporting product standardization and market transparency [30,31]. The regulation also introduces CE-marking requirements and harmonized product categories, ensuring minimum standards of safety, composition, and labeling prior to market placement. Despite this important regulatory advancement, challenges remain regarding the validation of agronomic performance claims, as the effectiveness of biostimulants is often highly variable under field conditions and strongly dependent on environmental and management factors. According to Regulation (EU) 2019/1009, plant biostimulants are defined by their functional claims rather than direct agronomic outputs. Specifically, their effects are limited to four main categories: enhancement of nutrient use efficiency, improvement of abiotic stress tolerance, improvement of crop quality traits, and increased availability of nutrients in the soil or rhizosphere. These regulatory functions provide the official framework for evaluating biostimulant activity within the European Union (Figure 1).

For biostimulant manufacturers to succeed in this evolving market, it is essential to provide reliable and high-quality experimental data to support their product claims. This data will not only benefit the producers but also offer valuable guidance to users seeking to maximize the benefits of biostimulant products [19]. Although plant biostimulants have been widely reviewed in the broader agricultural literature, their specific application to wheat has received less focused attention. In particular, the available literature lacks an integrated overview of the effects of biostimulants on wheat yield, grain nutritional quality, and resilience to abiotic stresses across both common and durum wheat. This review was designed to address this gap.

2. Materials and Methods

This systematic review was conducted in accordance with the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [32].

2.1. Search Strategy

A systematic literature search was conducted in two bibliographic databases: (Elsevier B.V., Amsterdam, The Netherlands; <https://www.scopus.com>) and Web of Science Core Collection (Clarivate Analytics, Philadelphia, PA, USA; <https://www.webofscience.com>) to identify primary studies on the application of plant biostimulants to wheat. The search combined three concept blocks with the Boolean operator AND: (i) the target crop (wheat and *Triticum* species); (ii) biostimulant categories, both microbial (PGPR/PGPB, nitrogen-fixing bacteria, arbuscular mycorrhizal fungi, *Trichoderma* spp., *Piriformospora indica* Sav. Verma, Aj. Varma, Rexer, G. Kost & P. Franken, beneficial fungi and bacteria) and non-microbial (humic and fulvic substances, seaweed extracts and *Ascomyces nodosum* (L.) Le Jolis, amino acids, chitin/nano-based and biochar-combined products); within each block, synonyms and word-stem truncations were combined with OR. Searches were restricted to peer-reviewed journal articles published in English between 2000 and 2026 and were run on 12 June 2026. The geographical distribution of the globally sourced studies that met all inclusion criteria is depicted in Figure 2.

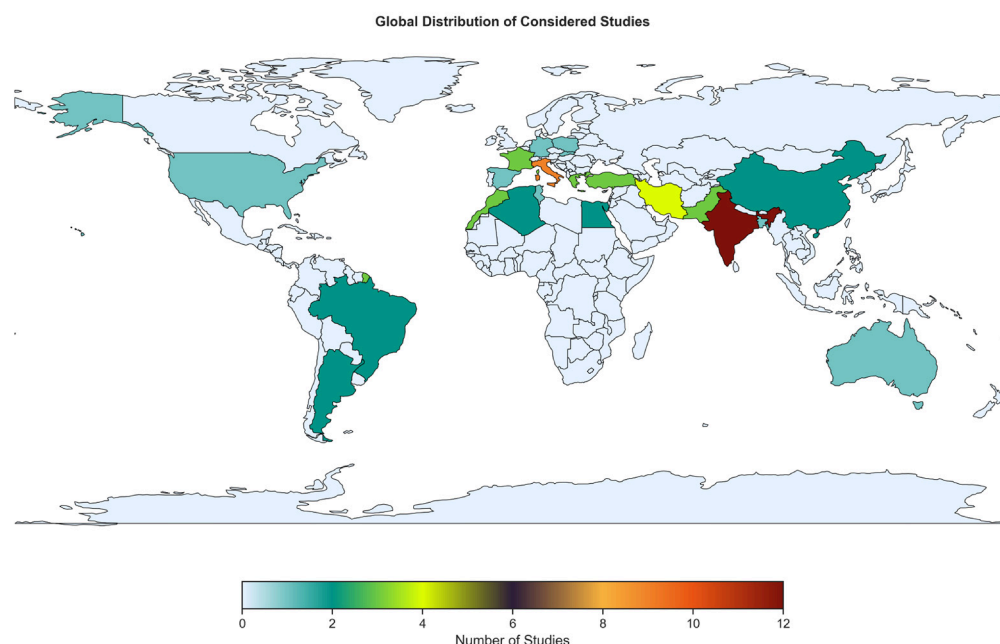


Figure 2. Distribution of studies considered.

2.2. Search Syntax

2.2.1. Scopus

TITLE-ABS-KEY (wheat OR "*Triticum aestivum*" OR "*Triticum durum*" OR "*Triticum turgidum*") AND (biostimulant* OR biofertiliz* OR "microbial inoculant*" OR "plant growth-promoting rhizobacteri*" OR PGPR OR PGPB OR "beneficial fung*" OR "beneficial bacteri*" OR "endophytic fung*" OR "humic acid*" OR "fulvic acid*" OR "humic substance*" OR "seaweed extract*" OR "seaweed sap" OR "*Ascomyces nodosum*" OR "arbuscular mycorrhiz*" OR *Azospirillum* OR *Azotobacter* OR *Trichoderma* OR "*Piriformospora indica*" OR nanochitin) AND PUBYEAR > 1999 AND PUBYEAR < 2027 AND DOCTYPE (ar) AND LANGUAGE (english).

2.2.2. Web of Science Core Collection

TS = (wheat OR "*Triticum aestivum*" OR "*Triticum durum*" OR "*Triticum turgidum*") AND (biostimulant* OR biofertiliz* OR "microbial inoculant*" OR "plant growth-promoting rhizobacteri*" OR PGPR OR PGPB OR "beneficial fung*" OR "beneficial bacteri*" OR "endophytic fung*" OR "humic acid*" OR "fulvic acid*" OR "humic substance*" OR "seaweed extract*" OR "seaweed sap" OR "*Ascomyces nodosum*" OR "arbuscular mycorrhiz*" OR *Azospirillum* OR *Azotobacter* OR *Trichoderma* OR "*Piriformospora indica*" OR nanochitin) AND PY = (2000–2026) AND DT = (Article) AND LA = (English). Records retrieved are show in Table 1 (live counts, 12 June 2026):

Table 1. Summary of database searches and applied limits. Records were identified from Scopus and Web of Science Core Collection by restricting the search to English-language articles published between 2000 and 2026. A total of 12,109 records were retrieved before deduplication and screening.

Database	Limits	Records
Scopus	2000–2026; Article; English	4988
Web of Science Core Collection	2000–2026; Article; English	7121
Total identified		12,109

2.3. Eligibility Criteria

Eligibility criteria were defined according to the population, intervention, comparator, outcomes, study design, timeframe, and language of publication. The review included primary studies conducted on wheat and assessing plant biostimulants under field, pot, or greenhouse conditions, provided that relevant agronomic, quality, nutritional, or abiotic stress-related outcomes were reported. Studies were excluded when wheat data were not separable from other crops, when no untreated or uninoculated control was included, or when the work consisted of reviews, meta-analyses, modeling studies, abstracts, or non-peer-reviewed literature. Only English-language articles published between 2000 and 2026 were considered (Table 2).

Table 2. Eligibility criteria used for study selection, including population, intervention, comparator, outcomes, study design, timeframe, and language restrictions.

Parameter	Inclusion	Exclusion
Population	Wheat— <i>Triticum aestivum</i> , <i>T. durum</i> / <i>turgidum</i>	Other crops; wheat data not separable
Intervention	Plant biostimulant—microbial (PGPR/PGPB, N-fixing bacteria, AMF, <i>Trichoderma</i> , <i>P. indica</i> , beneficial fungi/bacteria) or non-microbial (humic/fulvic substances, seaweed / <i>A. nodosum</i> , amino acids, chitin/nano, biochar-combined)	No biostimulant; mineral fertilizer, pesticide or PGR only
Comparator	Untreated/uninoculated control ($\pm$ standard fertilization)	No control or comparison
Outcomes	Grain yield/yield components; grain quality & nutrition (protein, N, macro/micronutrients, biofortification, gluten, etc.); and/or performance under abiotic stress (drought, salinity, heavy metals, temperature, nutrient deficiency)	Only molecular/biochemical endpoints with no agronomic, quality or stress outcome
Design/setting	Primary studies—open field and/or pot/greenhouse with relevant agronomic parameters	Reviews, meta-analyses, opinion; modeling-only; abstracts; non-peer-reviewed
Timeframe/language	2000–2026; English	Before 2000; non-English

2.4. Study Selection

Records from the two databases were combined and duplicates removed. Two reviewers independently screened titles and abstracts against the eligibility criteria; potentially eligible reports were then assessed in full text, with disagreements resolved by discussion. Reasons for full-text exclusion were recorded. The selection process and record counts are summarized in the PRISMA 2020 flow diagram (Figure 3). The PRISMA 2020 flow diagram was drawn as a vector graphic using a custom Python script (Python v3.11; <https://www.python.org>) and aesthetically refined with the support of artificial intelligence.

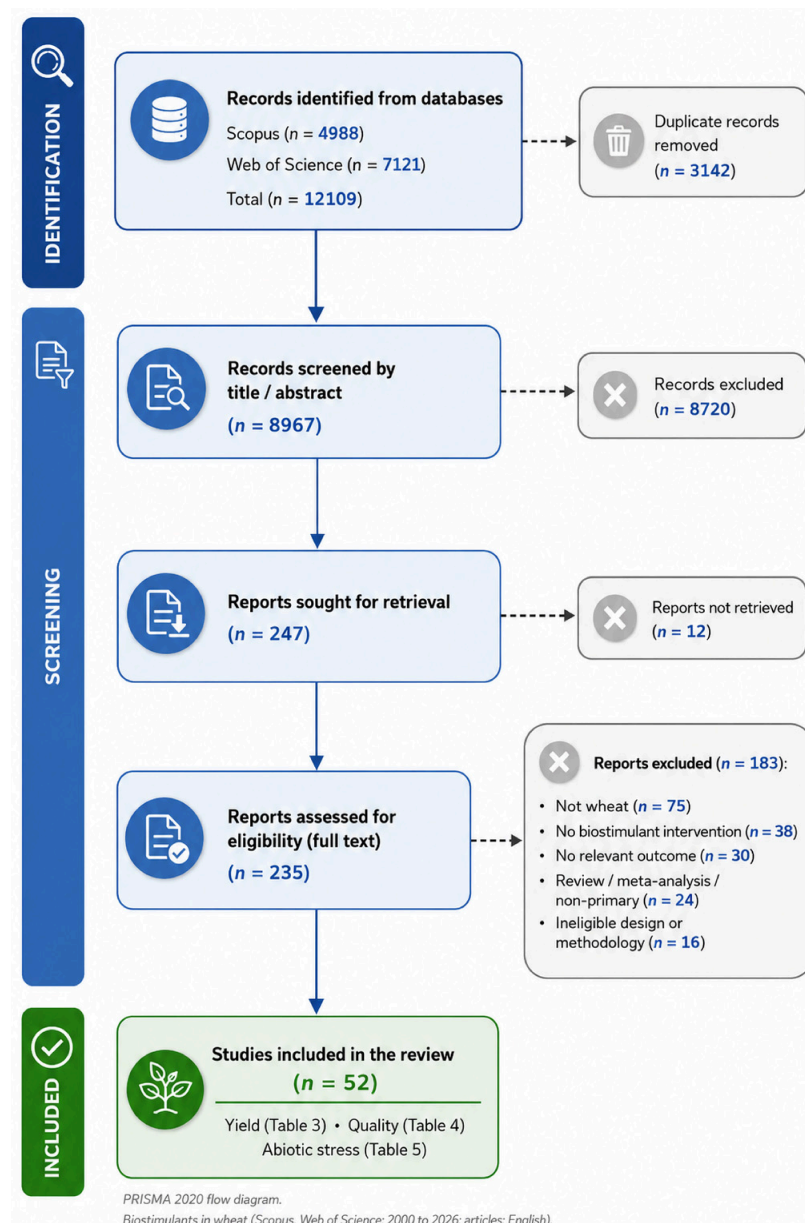


Figure 3. PRISMA 2020 flow diagram of the study selection process. Records were identified in Scopus ($n = 4988$) and Web of Science Core Collection ($n = 7121$); after removal of 3142 duplicates, 8967 records were screened by title and abstract and 235 full-text reports were assessed for eligibility. Fifty-two primary studies met all inclusion criteria and were included in the synthesis (Tables 3–5).

2.5. Data Extraction and Synthesis

For each included study the following were extracted: biostimulant type/category, wheat species and cultivar, experimental setting (field or pot/greenhouse), application method, and the reported effects on yield, grain quality/nutrition, and/or abiotic-stress tolerance. Given the heterogeneity of products, doses and endpoints, results were synthesized narratively and organized by outcome domain: grain yield (Section 3), grain quality (Sections 4 and 5) and performance under abiotic stress (Section 7). In addition to the narrative synthesis, a semi-quantitative analysis was conducted. For each biostimulant category, the range of reported grain yield responses relative to the control, and the number of studies reporting positive, neutral or context-dependent, and negative effects, were summarized (Tables S1 and S2).

3. Enhancing Grain Yield Through Biostimulant Applications

Across the 52 included studies, biostimulant application improved wheat performance in 46 studies (88%), produced neutral or strictly context-dependent effects in 6 (12%), and never produced a consistent yield penalty. Reported grain-yield increases spanned +6% to +123%, with the magnitude depending on biostimulant category, experimental setting and the level of abiotic stress (Table 3). Microbial products, particularly bacteria and microbial consortia, produced both the largest gains (up to +92% to +123% in nutrient-poor or drought conditions) and the widest variability, whereas non-microbial products gave more moderate but more consistent responses (humic and fulvic substances +11% to +21%; seaweed and plant extracts +17% to +29%; amino-acid and novel formulations +11% to +52%).

3.1. Microbial Biostimulants

Microbial biostimulants are increasingly acknowledged for their potential to improve crop yield and quality. Their use can significantly affect yield efficiency in agricultural production and is becoming more popular among farmers because of its ability to enhance crop productivity in an environmentally sustainable manner [33]. A study by Colla et al. [8] showed that coating durum wheat seeds with a microbial consortium containing the AMF *Glomus intraradices* N.C. Schenck & G.S. Sm. BEG72, *Glomus mosseae* Gerd. & Trappe, and *Trichoderma atroviride* Bissett MUCL45632 resulted in a notable increase in durum wheat yield compared to untreated seeds (by 32.1% and 8.3% during the first and second growing seasons, respectively). A study by Ayed et al. [34] further confirmed the potential of microbial biostimulants in durum wheat, showing that seed treatment with a consortium based on *Bacillus* spp., *Trichoderma* spp., and endomycorrhiza improved physiological performance, biomass, seed number per spike, thousand kernel weight, and grain yield under semi-arid field conditions. Among the application methods tested, the combined seed coating + foliar spray treatment was the most effective. The production of plant growth hormones such as gibberellic acid and indole-3-acetic acid is one mechanism through which beneficial fungi can enhance grain yield. Several studies have also reported that certain fungal strains associated with plant-beneficial effects may produce auxin-like compounds, promoting enhanced root development (e.g., increased root hair formation and deeper root systems), which supports seedling establishment and higher yield potential [35]. It should be noted that several fungal strains with plant growth-promoting activity are also regulated as Plant Protection Products (PPPs) under EU Regulation (EC) No. 1107/2009 when used for plant protection purposes. According to Foulkes et al. [36], a well-developed root system in wheat serves as the foundation for improved nutrient-use efficiency, ultimately influencing yield quantity and quality. This category of biostimulants can also produce siderophores, organic compounds capable of solubilizing micronutrients such as iron [8]. Similarly, a study conducted by Pagnani et al. [37] revealed that the double application of biostimulants containing a consortium of bacteria (including *Azospirillum brasilense* Tarrand, Krieg & Döbereiner strain Cd, *Gluconacetobacter diazotrophicus* (Döbereiner) Yamada, Hoshino & Ishikawa strain Pal5, *Herbaspirillum seropedicae* Baldani, Baldani & Döbereiner strain Z67, and *Burkholderia ambifaria* Vandamme, Holmes, Vancanneyt, Coenye, Hoste, Coopman, Revets, Lauwers, Gillis, Kersters & Govan gv VII strain PHP7) had a positive impact on durum wheat yield. This was evidenced by an increase in both the number of grains per spike and the number of spikes per square meter. These findings align with existing literature suggesting that the inoculation of N₂-fixing bacteria can lead to enhanced plant dry weight and grain yield [38] likely attributed to the N₂-fixation process [39] and auxin production, resulting in improved cereal yield [40,41]. A study conducted under field conditions on durum wheat showed that inoculation with a native bacterial consortium

based on *Bacillus cabrialesii* subsp. *cabrialesii* A. Ruiz-García et al. TE3T, *Priestia megaterium* (de Bary) Gupta et al. TRQ8, and *Bacillus paralicheniformis* Deng et al. TRQ65 improved grain yield under different N fertilization regimes, while grain quality remained substantially unchanged [42]; the response to the same native bacterial consortium was strongly influenced by N management, with positive effects mainly on early growth traits and N acquisition, whereas grain yield, grain quality, and N-use efficiency were affected more by N dose and fractionation than by inoculation [43].

PGPR, including genera such as *Azospirillum* and *Bacillus*, stimulate plant growth by producing hormones and facilitating nutrient uptake. A study by Silletti et al. [44] demonstrated that the rhizobacteria *Azotobacter chroococcum* Beijerinck and the fungus *Trichoderma harzianum* Rifai increased wheat yield under well-watered conditions with abundant nitrogen. These microorganisms also affected plant growth and nutrient status, suggesting an improvement in nutrient acquisition and assimilation, although the effects under nitrogen deficiency were treatment dependent. Another study by Roy et al. [45] highlighted how native soil microorganisms, such as *Candida tropicalis* (Castell.) Berkhout *Actinomucor elegans* (Eidam) C.R. Benj, and *Delftia lacustris* (S. W. K. Lee et al.) Wen et al., significantly increased seed yield and nutrient concentration in wheat thanks to their multiple plant growth-promoting traits, such as phytohormone production, extracellular enzyme activity, siderophore production, and mineral solubilization. Ramesh et al. [46] described how seed inoculation with microbial strains improves the rhizospheric ecosystem, redistributing nutrient pools within the soil and thereby enhancing nutrient availability. This process ultimately leads to increased plant growth and seed yield under various cropping systems. The study emphasized that microbial enzymatic activities and other plant growth-promoting traits (like phytohormone production, siderophore release, and mineral solubilization) in the rhizosphere play a significant role in stimulating plant growth and increasing seed yield. Bechtaoui et al. [47] showed under field conditions that inoculation with PGP rhizobacteria and rhizobial strains, alone or in combination, improved phosphorus uptake, shoot and root biomass, and spike weight in durum wheat, with the strongest effect generally observed in plants inoculated with rhizobia or with the combined PGP-rhizobia treatment. Gazoulis et al. [48] reported that a microbial biostimulant based on phosphate- and potassium-solubilizing bacteria, when applied in combination with reduced basal fertilization and post-emergence herbicide, increased P and K concentrations in durum wheat tissues, improved grain yield and yield components, and reduced weed biomass compared with conventional fertilization alone. Chami et al. [49] showed that seed inoculation of durum wheat with *Paenibacillus polymyxa* (Prazmowski) Ash et al. strains improved plant growth and productivity, with the co-inoculation treatment producing the strongest increase in grain yield and yield components compared with the non-inoculated control.

Bio-fortification, especially with micronutrients like Zn and Fe, is gaining attention as a sustainable approach to improving the nutritional quality of major food crops. PGPR plays a crucial role in this process by mobilizing nutrients through various mechanisms, including acidification, chelation, exchange reactions, and the release of organic acids. A study by Abaid-Ullah et al. [50] investigated the effects of Zn-solubilizing rhizobacteria on common wheat yield. The results showed that PGPRs significantly enhanced grain yield by increasing the number of grains per spike and tillers per plant. The increased availability of Zn in the soil, due to the solubilization of Zn bound by organic acids produced by the bacteria, was a key factor contributing to the improved yield and Zn concentration in wheat grains.

The various studies summarized here demonstrate the significant role of PGPR in enhancing grain yield through different mechanisms, including nutrient solubilization,

phytohormone production, and symbiotic interactions with fungi like AMF. The effectiveness of these biostimulants depends on several factors, including microbial strain, nutrient availability, and environmental conditions, highlighting the need for targeted application strategies to maximize agricultural productivity. The effect of biostimulants on plant growth comes from the synergism of many components at different concentrations. This aligns with existing literature indicating that biostimulants function by enhancing plant mineral uptake and improving nutrient use efficiency [17,18,51]. A study by Abdolmaleki et al. [52] investigated the effect of a fungal consortium, including *P. indica* and *Trichoderma longibrachiatum* Rifai, on common wheat under different light intensities. The consortium mitigated the negative impact of reduced light, significantly increasing the number of seeds and grain yield under low light conditions. The fungi improved plant growth and yield by helping plants cope with abiotic stress. In particular, *Trichoderma* species can produce indole-3-acetic acid (IAA), a hormone that regulates plant growth under stress conditions and enhances the host plant's tolerance to abiotic stresses [53]; while *P. indica* can decrease Na⁺ uptake under salinity stress and increase K⁺ uptake [54], boosting plant growth and improving soil fertility [55].

These results are consistent with those of Sharma et al. [56], who found a positive effect of *Trichoderma* on grain yield. Another study by Sobhani et al. [57] examined the combined effects of biochar and AMF on wheat yield. AMF enhances nutrient uptake, particularly under stress conditions, by improving root morphology and expanding hyphal networks. The combination of AMF with biochar showed the potential to improve grain yield by optimizing both water and nutrient uptake. Grain yield is greatly influenced by nutrient availability and interactions with beneficial microorganisms such as AMF and bacteria of the genus *Azospirillum*. According to a study by Pellegrino et al. [58] and Shabani et al. [59], mycorrhizal symbiosis enhances nutrient uptake, particularly of P and Zn, by spreading hyphae that increase root surface area and improve nutrient transport to the plant. This symbiosis also alters root morphology, improving the uptake of nitrogen from fertilizers. By enhancing water and nutrient absorption, mycorrhizal associations boost photosynthesis, ultimately increasing grain yield. Silva et al. [60] examined the influence of AMF and *Azospirillum* on grain yield, particularly under varying zinc fertilization conditions. The study found that inoculation with *A. brasilense* combined with appropriate residual Zn rates enhanced root colonization by AMF, improved plant nutrition, and increased grain yield. However, the effectiveness of this treatment was contingent on balancing fungal colonization with Zn availability. This highlights the importance of carefully managing fertilization practices to maximize the benefits of microbial inoculation on grain yield. Similarly, Raklami et al. [61] showed under open-field conditions that inoculation with a microbial consortium composed of PGPR, rhizobia, and AMF improved growth, nutrient accumulation, and productivity in durum wheat, with the strongest effect observed under the combined treatment, which markedly increased shoot and root biomass as well as spike number and spike weight.

Considered together (Table S1), microbial biostimulants were the category with both the largest and the most variable yield responses. Single-strain bacterial inoculants (PGPR and PGPB, including nitrogen-fixing genera such as *Azospirillum*, *Azotobacter*, *Herbaspirillum*, *Klebsiella*, *Enterobacter*, *Bacillus* and *Paenibacillus*) increased grain yield by +9% to +96% (twelve of thirteen studies positive), with the largest relative gains under low or reduced nitrogen and under salinity; responses were smallest or non-significant on fertile field soils and were strongly genotype-dependent in ancient wheats. Arbuscular mycorrhizal fungi increased grain yield by more than +20% and grain iron by up to +63%, with larger effects at low soil nitrogen (both studies positive). Beneficial fungi (*Trichoderma*, *P. indica* and other endophytes) increased grain yield by +29% to +48% where yield was measured

and consistently alleviated salinity and light-limitation stress (five of five studies positive). Microbial consortia combining bacteria and fungi, or AMF and PGPR, showed the widest range of all, from +6% to +123% (nine of twelve studies positive); the largest gains occurred under nutrient-deficient or drought conditions and in pot or greenhouse trials, whereas some field studies were inconsistent across sites.

3.2. Non-Microbial Biostimulants

Humic acid (HA) is a naturally occurring polymeric-heterocyclic organic compound containing carboxylic (COOH^-), phenolic (OH^-), alcoholic, and carbonyl fractions [62]. HA can improve photosynthesis and respiration rates in plants, as well as stimulate hormone and protein production (Table 3). Research indicates that this compound positively influences common wheat growth and yield by enhancing nutrient uptake [63]. Delfine et al. [64] reported that applying HA via foliar spray resulted in a transitional increase in dry mass production of durum wheat compared to unfertilized controls and split soil nitrogen application. This effect was also evident in grain yield, spike fertility, and grain protein content. The study concluded that HA had limited but positive effects on plant growth, grain yield, quality, and photosynthetic metabolism of durum wheat cultivated in a Mediterranean-type agroecosystem in southern Italy. Mutlu and Tas [65] reported that foliar application of humic acid in organically grown durum wheat significantly improved chlorophyll index, flag leaf area, plant height, grain yield, and grain protein ratio, with the best response obtained at 4.5 L ha^{-1} applied at heading stage. HA is recognized for its ability to enhance water penetration into seeds, promote germination, and stimulate root growth [66].

Amino acid-based biostimulants obtained from the enzymatic hydrolysis of plant extracts also showed positive effects in durum wheat. In a three-year no-tillage field trial under semi-arid Mediterranean conditions, foliar application of these products, alone or combined with slow-release urea, increased spike number, grain yield, and total protein production, with the magnitude of the response varying among seasons according to rainfall distribution [67].

Seaweed extracts, such as those from *A. nodosum*, have been used as biostimulants to promote plant growth. Seaweed concentrates are known to have many beneficial effects on plants as they contain growth-promoting hormones, trace elements, vitamins, and amino acids [68].

Stamatiadis et al. [69] examined the effect of an *A. nodosum* extract on wheat under different water and nitrogen levels. A further three-year field study by Stamatiadis et al. [70] showed that a single foliar application of *A. nodosum* extract increased grain yield, grain N, P and K accumulation, and N-use efficiency in winter durum wheat, with the strongest average response at tillering, although the optimal application stage varied among site-years. SE improved nutrient uptake and yield only when nitrogen fertilizer was present, highlighting its role in enhancing the efficiency of nutrient use under specific conditions.

In a study by Soliman et al. [71], the use of biochar and selenium-chitosan nanoparticles (Se-NPs) was explored to mitigate the effects of soil salinity on wheat plants. The study found that these biostimulants played a crucial role in protecting the plants by reducing Na^+ accumulation in the leaves, which typically causes oxidative and osmotic damage. While neither biochar nor Se-NPs alone significantly affected grain yield under normal conditions, their combined application significantly improved grain yield under salt-stressed conditions by enhancing plant growth and biomass production.

Previous research has shown that the use of plant biostimulants enhances leaf pigmentation and photosynthetic efficiency, initiating various molecular and physiological mechanisms that lead to increased nutrient use efficiency, yield, and quality [63,72]. These

findings suggest that biostimulants can play a crucial role in optimizing crop production by increasing nutrient uptake, chlorophyll content, PSII maximum quantum efficiency, photosynthesis rate, generative shoots, seed weight, plant growth, and overall yield [8,66,73–81]. By leveraging the benefits of biostimulants, farmers can optimize their crop production and achieve higher yields.

Among the non-microbial products (Table S1), yield responses were more moderate but more consistent. Humic and fulvic substances produced grain yield gains of +11% to +21% (five of six studies positive), together with improvements in protein and micronutrient status, most evident in combination with nitrogen or potassium and under salinity. Seaweed and plant extracts, mainly from *A. nodosum*, *Sargassum*, *Ulva* and *Codium*, increased grain yield by +17% to +29% (five of six studies positive), in a dose-dependent manner and often contingent on adequate nitrogen and water. Amino acid and protein hydrolysate products, together with novel formulations such as Glutacetine, nanochitin and selenium–chitosan nanoparticles, raised yield by +11% to +52% (eight of eight studies positive), with larger relative effects under controlled conditions and clear dose and cultivar dependence. None of the non-microbial categories produced a consistent negative effect on yield.

Table 3. Biostimulants were investigated to improve wheat yield.

Biostimulants	Effects	Reference
<i>Klebsiella</i> sp. SBP-8	Mitigate salt stress	[77]
<i>Glomus intraradices</i> N.C. Schenck & G.S. Sm. BEG72, <i>Glomus mosseae</i> Gerd. & Trappe, and <i>Trichoderma atroviride</i> Bissett MUCL 45632	Enhanced grain quality (increased protein, K, P, Fe, and Zn concentrations) and yield stability	[8]
<i>Azotobacter chroococcum</i> Beijerinck and <i>Trichoderma harzianum</i> Rifai	Water and Nitrogen deficiency	[44]
<i>Candida tropicalis</i> (Castell.) Berkhout (PY1), <i>Actinomucor elegans</i> (Eidam) C.R. Benj. (PT1), and <i>Delftia lacustris</i> S.W.K. Lee et al. (IS5)	Impact of PGPM on growth and yield of durum wheat	[45]
<i>Serratia liquefaciens</i> (Grimes & Hennerty) Bascomb et al., <i>Serratia marcescens</i> Bizio, and <i>Bacillus thuringiensis</i> Berliner	Improve yield and quality of common wheat	[50]
<i>Paenibacillus polymyxa</i> (Prazmowski) Ash et al. SGH1, SGK2	Improved plant growth, yield components, and grain yield	[49]
<i>Piriformospora indica</i> Sav. Verma, Aj. Varma, Rexer, G. Kost & P. Franken, <i>Trichoderma longibrachiatum</i> Rifai	Improve growth and yield of common wheat	[52]
<i>Rhizophagus irregularis</i> (Błaszk., Wubet, Renker & Buscot) C. Walker & A. Schüßler	increases mineral nutrient uptake	[57]
<i>Trichoderma harzianum</i> Rifai	Growth promotion effects on rootlets, tillers, the weight of grains, and grain yield	[56]
<i>Piriformospora indica</i>	Plant stress tolerance	[55]
<i>Azospirillum brasilense</i> Tarrand, Krieg & Döbereiner, <i>Gluconacetobacter diazotrophicus</i> (Döbereiner) Yamada, Hoshino & Ishikawa, <i>Burkholderia ambifaria</i> Vandamme et al., and <i>Herbaspirillum seropedicae</i> Baldani, Baldani & Döbereiner	Enhancement of yield and photosynthetic efficiency	[37]
<i>Bacillus</i> spp., <i>Trichoderma</i> spp., and endomycorrhiza	Improved biomass, seed number per spike, thousand kernel weight, and grain yield under semi-arid conditions	[34]

Table 3. Cont.

Biostimulants	Effects	Reference
<i>Azotobacter</i> and Mycorrhiza	Plant nutrition and growth	[40]
<i>Herbaspirillum seropedicae</i> Baldani, Baldani & Döbereiner	Effects on plant growth and increase crop productivity	[41]
<i>Claroideoglomus etunicatum</i> (W.N. Becker & Gerd.) C. Walker & A. Schüßler, <i>Funneliformis mosseae</i> (T.H. Nicolson & Gerd.) C. Walker & A. Schüßler, <i>Rhizophagus intraradices</i> (N.C. Schenck & G.S. Sm.) C. Walker & A. Schüßler	Increased biomass, Increased grain yield, Improved nutrient content (P, N, Zn), Positive overall effect of AMF inoculation in field wheat trials	[58]
<i>Bacillus cabrialesii</i> subsp. <i>cabrialesii</i> A. Ruiz-García et al. TE3T + <i>Priestia megaterium</i> (de Bary) Gupta et al. TRQ8 + <i>Bacillus paralicheniformis</i> Deng et al. TRQ65	Increased grain yield in durum wheat, Improved performance under different nitrogen fertilization rates, Enhanced crop productivity under reduced N input, Synergistic effect of bacterial consortium	[42]
<i>Azospirillum brasilense</i> Tarrand, Krieg & Döbereiner	Effect on fungal root colonization and yield of wheat–maize	[60]
<i>Enterobacter cloacae</i> Jordan 1890	Nutrient acquisition and growth	[46]
PGPR + rhizobia	Improved phosphorus uptake, biomass, and spike weight of durum wheat under field conditions	[47]
PGPR + rhizobia + AMF	Improved biomass, nutrient accumulation, spike number, and spike weight of durum wheat under open-field conditions	[61]
Humic acid	Effect on growth and crop nutrient	[62]
Humic acid	Yield and nutrient contents of wheat	[63]
Humic acid	Positive effects on dry mass accumulation, grain yield, spike fertility, and grain protein content	[64]
Humic acid	Improved chlorophyll index, flag leaf area, plant height, grain yield, and grain protein ratio; best response at heading stage	[65]
Humic acid	Beneficial effects of humic acid on micronutrient availability	[78]
<i>Ascophyllum nodosum</i> (L.) Le Jolis	Growth, nutrient uptake, and yield of winter wheat	[69]
<i>Ascophyllum nodosum</i>	Increased grain yield, grain N, P and K accumulation, and N-use efficiency	[70]
<i>Codium fragile</i> (Suringar) Hariot + <i>Opuntia ficus-barbarica</i> A. Berger extracts	Improved root length, chlorophyll content, grain yield	[79]
Selenium-chitosan nanoparticles	Grain production and protection from salt stress	[71]
Glutacetine	N uptake and remobilization, seed yield, and grain quality	[72]
Amino acids	Effect on the growth, yield, and the grain quality of winter wheat	[73]

Table 3. Cont.

Biostimulants	Effects	Reference
Amino acids	Increased spike number, grain yield	[67]
Marine biostimulant and fungal extract	Improved grain yield, nitrogen uptake, and nitrogen allocation to ears in durum wheat	[80]
Seaweed extracts, glycine betaine, micronized vaterite, PGPB	Improved root development, chlorophyll content, grain yield, and nitrogen use efficiency	[81]

4. Biostimulant Effects on Grain Quality

Biostimulants, encompassing both microbial agents such as PGPR and AMF, as well as non-microbial products like SE, humic substances, and nano-based materials, significantly impact the quality traits of wheat (Table 4). These biostimulants enhance nutrient uptake, protein synthesis, and the bioavailability of essential macro- and micronutrients, improving critical quality parameters such as protein content, nitrogen levels, phosphorus and potassium concentrations, and micronutrient biofortification (zinc, iron). Additionally, they influence other technological quality traits including gluten content, bulk density, and falling number. This breakdown categorizes the effects of biostimulants on wheat grain quality based on these key characteristics.

4.1. Protein Content and Nitrogen

One of the primary effects of biostimulants is their ability to enhance protein content in wheat grains, mainly due to their role in improving nitrogen uptake. Nitrogen is essential for amino acid and protein synthesis, and biostimulants such as PGPR and AMF significantly increase nitrogen availability to plants through various mechanisms.

In several studies, inoculation with PGPR has resulted in substantial increases in grain protein content (GPC). For example, a consortium of PGPR, including *A. brasilense*, *G. diazotrophicus*, *H. seropedicae*, and *B. ambifaria*, was applied to ancient wheat varieties such as Senatore Cappelli, Saragolla, and Molisano. The results showed that GPC increased by 19.2% to 32.1%, depending on the variety, compared to untreated controls [37]. The enhanced protein synthesis was attributed to the ability of these PGPRs to fix atmospheric nitrogen, thereby increasing nitrogen uptake by the wheat plants. This improved nitrogen assimilation led to increased protein synthesis in the grains. Another study demonstrated that inoculation with *Azospirillum* and *Azotobacter* strains not only improved nitrogen fixation but also increased root development, leading to higher nitrogen absorption and a subsequent increase in protein content [82]. In field trials, inoculation with *A. brasilense* resulted in higher biomass production and grain yield, with a significant increase in nitrogen content, which was directly linked to higher GPC. The underlying mechanism involved the production of phytohormones such as IAA, which stimulated root growth, enhancing the plant's ability to absorb nitrogen from the soil [83].

AMF also plays a critical role in improving nitrogen uptake and, consequently, grain protein content. By forming symbiotic relationships with wheat roots, AMFs extend their hyphal networks into the soil, facilitating more excellent nitrogen absorption. This symbiosis has been shown to significantly increase nitrogen concentration in grains, particularly when AMF is co-inoculated with PGPR. In a study conducted across seven locations characterized by low nitrogen inputs, the combined use of AMF and PGPR significantly boosted nitrogen uptake and protein content compared to untreated controls, with increases of up to 31% in nitrogen concentration [84,85].

Laurent et al. [80] reported that foliar application of a marine biostimulant and a fungal extract in durum wheat increased total plant N, enhanced N allocation to the ears, and promoted N remobilization during grain filling, indicating a positive effect on nitrogen dynamics that may support grain quality improvement. Consistent with this, Rossini et al. [81] found that foliar biostimulant treatments based on seaweed extracts, glycine betaine, micronized vaterite, and beneficial bacteria increased grain protein content in rainfed durum wheat and improved crop performance particularly under reduced N fertilization. Rossini et al. [79] also found that foliar application of *Codium fragile* (Suringar) Hariot and *Opuntia ficus-barbarica* A.Berger extracts or micronized vaterite increased grain protein content in durum wheat, whereas the other tested biostimulants showed more limited effects on this trait.

Foliar amino acid-based biostimulants, applied alone or together with slow-release urea, increased grain protein concentration in the driest season and enhanced total protein production in durum wheat, suggesting improved nitrogen use efficiency [67].

4.2. Macronutrients

Biostimulants are also highly effective in enhancing the uptake of macronutrients, particularly P and K, both of which are essential for plant metabolism, growth, and grain development. Phosphorus is a key element in energy transfer, and its availability is crucial for various metabolic processes that influence grain yield and quality. PGPR, especially phosphorus-solubilizing bacteria such as *Bacillus megaterium* de Bary 1884, play a pivotal role in increasing P availability. These bacteria produce organic acids that solubilize insoluble phosphate compounds in the soil, making phosphorus more bioavailable for plant uptake. In a field study, inoculation with *B. megaterium* increased P content in wheat grains by 31% compared to control treatments [69,86]. Similarly, co-inoculation with phosphate-solubilizing bacteria and AMF significantly enhanced P uptake. AMF secrete phosphatases that convert phosphorus into plant-accessible forms, while their extensive hyphal networks enable the plant to access phosphorus from a larger volume of soil [87,88]. The increase in phosphorus absorption has been shown to double its concentration in grains in some cases [89].

Both microbial and non-microbial biostimulants similarly enhance potassium uptake. AMF's extended hyphal networks facilitate K uptake, a key nutrient for enzyme activation, water regulation, and carbohydrate transport within the plant. Co-inoculation with AMF and PGPR has been shown to increase potassium concentrations in wheat grains significantly. For instance, a study involving *Pseudomonas putida* (Trevisan 1889) Migula 1895 and *Pseudomonas fluorescens* Migula 1895 strains showed notable increases in K uptake, particularly in plants co-inoculated with AMF, where potassium concentration increased by up to 23% [90]. Non-microbial biostimulants such as SE and humic substances have also demonstrated the ability to improve potassium levels, further enhancing the overall nutritional profile of wheat grains.

4.3. Micronutrient

One of the most significant contributions of biostimulants to wheat grain quality is micronutrient biofortification, particularly with Zn, Fe, Mn, and Cu. Micronutrient deficiencies are a major public health concern, and wheat biofortification with these elements is crucial for improving nutritional outcomes in populations reliant on wheat as a staple food. PGPR has shown considerable potential in enhancing the bioavailability of Zn, which is essential for numerous enzymatic processes in both plants and humans. In a study examining zinc-solubilizing PGPR strains such as *Serratia liquefaciens* (Grimes e Hennerty 1931), *Bacillus thuringiensis* Berliner 1915, and *Serratia marcescens* Bizio 1823, Zn content in wheat

grains increased from 33.0 mg/kg in the control to 54.1 mg/kg in PGPR-treated plants, outperforming even zinc fertilizer treatments [50]. This improvement was due to the bacteria's ability to solubilize Zn through the production of organic acids like gluconic acid, which chelate insoluble zinc compounds, making them available for plant absorption. The same study also reported increased Mn and Fe uptake, highlighting the multifunctionality of PGPR in biofortifying wheat grains with multiple essential micronutrients.

AMF also contributes significantly to micronutrient biofortification, particularly with Fe and Zn. AMF enhances the uptake of these nutrients by extending their hyphae into the soil and accessing otherwise unavailable pools of micronutrients. In a two-year field experiment on durum wheat, AMF inoculation increased iron and zinc concentrations by 63% and 101%, respectively [86]. The increase in micronutrient uptake is particularly valuable in regions where soils are deficient in these elements, as AMF can improve the nutritional quality of wheat grains through enhanced biofortification. Moreover, combined inoculation of AMF and PGPR has been shown to have synergistic effects on micronutrient uptake. Nano-based biostimulants such as nanochitin have also been shown to enhance the uptake of micronutrients, particularly zinc and iron. In one study, the application of nanochitin increased GPC by 33.4% and Zn content by 22.1% [91]. These results suggest that nano-based biostimulants could play an essential role in future biofortification strategies.

5. Other Grain Quality Traits

In addition to nutrient content, biostimulants also influence other critical grain quality traits such as gluten content, bulk density, and falling number, which are important for wheat's technological properties, including its milling and baking quality (Table 4).

Seaweed extracts, for instance, have been shown to maintain or slightly improve grain quality parameters such as protein content, gluten strength, bulk density, and falling number. In a multi-year study on durum wheat, seaweed extracts containing high levels of *L*-amino acids and humic substances were found to increase gluten content and bulk density, although the changes were not always statistically significant [6]. The formulation containing high nitrogen, sulfur, and magnesium content led to the highest increases in gluten content and protein levels, while the *L*-amino acid-rich formulation showed the greatest impact on bulk density and falling number, which is an important measure of the wheat's baking quality.

Furthermore, the combination of humic substances with SE has demonstrated a positive effect on wheat's gluten strength and protein content, particularly when applied alongside nitrogen fertilizers. This combination also improved bulk density and technological properties, which are key to determining the commercial value of common wheat [92].

Overall, biostimulants have shown a consistent and significant impact on various quality traits of wheat grains, particularly in terms of protein content, nitrogen levels, macronutrient concentrations, and micronutrient biofortification. Through a range of mechanisms—including nitrogen fixation, phosphate solubilization, and enhanced root colonization—biostimulants contribute to improved nutrient uptake, protein synthesis, and grain quality. Biofortification with micronutrients such as Zn and Fe is particularly important for addressing global nutritional deficiencies, and the positive results from biostimulant applications underscore their potential in this regard. Nevertheless, the effects of biostimulants are the result of complex processes influenced by a variety of factors, including environmental conditions, soil fertility, water availability, and the specific combinations of wheat varieties and biostimulant strains. Therefore, optimizing their use for maximum benefit requires careful consideration of these interacting factors, but the promise they hold for improving both wheat productivity and nutritional quality is undeniable.

Table 4. Biostimulants investigated to improve grain quality.

Biostimulants	Effects	Reference
<i>Azospirillum brasilense</i> Tarrand, Krieg & Döbereiner, <i>Gluconacetobacter diazotrophicus</i> (Döbereiner) Yamada, Hoshino & Ishikawa, <i>Burkholderia ambifaria</i> Vandamme et al., and <i>Herbaspirillum seropedicae</i> Baldani, Baldani & Döbereiner	Optimization of nutrient uptake and physiological traits	[37]
PGPR (<i>Azospirillum brasilense</i> strain BNM-10)	Increased biomass, grain yield, nitrogen uptake, and grain protein concentration	[83]
AMF consortium (<i>Claroideoglomus etunicatum</i> (W.N. Becker & Gerd.) C. Walker & A. Schüßler, <i>Glomus intraradices</i> N.C. Schenck & G.S. Sm.), PGPR (<i>Pseudomonas jessenii</i> R62, <i>Pseudomonas synxantha</i> R81)	Increased grain yield, Improved grain protein content, Enhanced mineral nutrition (P, K, Cu, Fe, Zn, Mn), Synergistic effect of AMF + PGPR	[84]
<i>Claroideoglomus etunicatum</i> , <i>Funneliformis mosseae</i> (T.H. Nicolson & Gerd.) C. Walker & A. Schüßler, <i>Rhizophagus intraradices</i> (N.C. Schenck & G.S. Sm.) C. Walker & A. Schüßler	Increased biomass, Increased grain yield, Improved nutrient content (P, N, Zn), Positive overall effect of AMF inoculation in field wheat trials	[58]
Specific <i>Pseudomonas</i> strains (R62, R81, R103, R110), indigenous AMF consortium	Increased grain yield, Increased grain protein content, Improved phosphorus and iron content, Alteration of rhizobacterial community structure, Effects influenced by growth stage and fertilization	[85]
<i>Rhizophagus irregularis</i> (Błaszk., Wubet, Renker & Buscot) C. Walker & A. Schüßler (DAOM197198)	Increased grain iron (Fe) concentration, Increased grain zinc (Zn) concentration, Improved micronutrient uptake in durum wheat, Stable effect across different soil nitrogen levels	[86]
<i>Pseudomonas fluorescens</i> Migula strain 153 and 169, and <i>Pseudomonas putida</i> (Trevisan) Migula strains 4 and 108	Increased grain yield, Improved nutrient uptake (N, P, K), Enhanced phosphorus acquisition, Improved wheat growth under greenhouse and field conditions	[87]
<i>Serratia liquefaciens</i> (Grimes & Hennerty) Bascomb et al., <i>Serratia marcescens</i> Bizio, and <i>Bacillus thuringiensis</i> Berliner	Improved wheat yield, Improved grain quality, Enhanced plant growth, Improved nutrient utilization	[50]
Seaweed Extract; Humic acid	Increased grain yield, Improved grain quality traits, Enhanced productivity of durum wheat, Positive biostimulant effects of organic extracts	[6]
Nanochitin	Increased grain yield, Improved grain quality, Enhanced growth of winter wheat, Positive biostimulant effects on agronomic traits	[91]
Amino acids-based biostimulant	Increased grain protein concentration, Improved grain yield and quality, Enhanced nitrogen metabolism, Better performance under semi-arid no-tillage conditions	[67]

Table 4. Cont.

Biostimulants	Effects	Reference
Seaweed extract and humic acid	Increased grain yield, Increased protein content, Improved mineral content (K, P, Zn), Improved gluten content, Modified fatty acid profile in grains	[92]
<i>Codium fragile</i> (Suringar) Hariot extract; <i>Opuntia ficus-indica</i> (L.) Mill. extract	Increased grain protein content, Increased test weight (hectoliter weight), Improved grain quality of durum wheat, Positive agronomic responses under Mediterranean field conditions	[79]
Marine biostimulant and fungal extract	Enhanced total plant N, N allocation to ears, and N remobilization during grain filling	[80]
Seaweed extracts, glycine betaine, micronized vaterite, PGPB	Increased grain protein content and test weight in rainfed durum wheat	[81]

6. Effect of Biostimulants on Secondary Metabolism

Biostimulants have been increasingly recognized not only for their effects on plant growth and yield, but also for their ability to modulate plant secondary metabolism. Secondary metabolites, including phenolic compounds, flavonoids, alkaloids, terpenoids, and phytoalexins, play a crucial role in plant defense mechanisms, stress tolerance, and overall plant fitness.

Recent studies have demonstrated that biostimulants can significantly influence the biosynthesis and accumulation of these compounds through the activation of specific metabolic pathways. Microbial biostimulants such as plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) are known to induce metabolic reprogramming in plants, leading to enhanced production of secondary metabolites involved in plant defense and adaptation [93,94].

One of the primary mechanisms underlying this effect is the activation of the phenylpropanoid pathway, which is responsible for the synthesis of key compounds such as flavonoids, lignin, and phenolic acids. These metabolites contribute to strengthening plant cell walls, scavenging reactive oxygen species (ROS), and improving resistance to abiotic stresses. For instance, microbial inoculation has been shown to enhance flavonoid biosynthesis and amino acid-derived pathways (e.g., phenylalanine, tyrosine, and tryptophan metabolism), which are closely linked to stress signaling and plant defense responses [93].

In wheat, metabolomic studies have confirmed that biostimulant treatments can alter the biochemical profile of plants, leading to increased accumulation of bioactive compounds. For example, the combined application of microbial biostimulants and elicitor molecules such as laminarin has been shown to induce a shift toward defense-related secondary metabolites, including phenylpropanoids and benzoxazinoids, which are associated with enhanced resistance to environmental stresses and pathogens [95].

Furthermore, non-microbial biostimulants, such as seaweed extracts and humic substances, have also been reported to stimulate the synthesis of secondary metabolites. These products contain bioactive compounds, including phytohormones and signaling molecules, which can trigger metabolic pathways associated with antioxidant production and stress tolerance. Secondary metabolites act as signaling molecules, enzyme regulators, and protective compounds, contributing to improved plant resilience and adaptation under adverse environmental conditions [96].

The enhancement of secondary metabolite production is closely linked to improved antioxidant capacity in plants. Biostimulants promote the accumulation of compounds such as phenolics and flavonoids, which play a key role in mitigating oxidative stress by neutralizing ROS generated under stress conditions such as drought, salinity, and extreme temperatures. This metabolic adjustment contributes to maintaining cellular homeostasis and protecting photosynthetic machinery.

Despite these promising findings, the effects of biostimulants on secondary metabolism are highly dependent on several factors, including the type of biostimulant, plant genotype, environmental conditions, and application methods. Moreover, the underlying molecular mechanisms are not yet fully understood, and further research integrating metabolomics, transcriptomics, and proteomics approaches is needed to elucidate the complex interactions between biostimulants and plant metabolic networks [97].

Overall, the modulation of secondary metabolites represents a key mechanism through which biostimulants enhance plant performance, contributing not only to stress tolerance but also to the nutritional and functional quality of wheat.

The use of biostimulants in wheat production raises important questions regarding their agronomic applicability and economic viability at field scale. Wheat is cultivated over extensive areas and typically provides relatively low profit margins per hectare compared with horticultural crops. Consequently, farmers' adoption decisions are strongly influenced by the cost–benefit ratio and the consistency of yield responses to additional inputs.

Despite these agronomic benefits, the economic performance of biostimulants in wheat remains highly variable. Field studies consistently report that yield increases are not always stable across environments, with strong interactions between soil properties, climate conditions, crop management practices, and product formulation [18,98]. This variability limits predictable return on investment, which is a key barrier to large-scale adoption in low-margin cereal systems.

In contrast, biostimulants are more widely adopted in high-value horticultural crops, where higher economic returns per unit area justify additional input costs. However, under stress-prone or low-fertility conditions, even moderate improvements in wheat yield or nutrient efficiency may result in economically meaningful gains when applied over large, cultivated areas [25].

Overall, while biostimulants are agronomically effective under specific conditions, their economic viability in wheat depends strongly on environmental context and management practices. Further multi-year field trials and robust cost–benefit analyses are still required to support large-scale adoption in cereal-based systems.

7. Effect of Biostimulants on Stressed Plant

7.1. Drought Stress

Plant water deficits are caused by atmospheric drought, which is caused by high temperatures, low air humidity, or increased water transpiration (Table 5). Drought affects plants in various ways, such as physiologically, morphologically, and biologically [98]. In a field study on drip-irrigated durum wheat under semi-arid conditions, the combined application of native AMF, *Bacillus*-based PGPR, and compost improved shoot and root biomass, grain and straw yield, photosynthetic traits, and oxidative stress tolerance under drought stress, with the most consistent benefits generally observed in combined treatments [99].

During periods of water stress, the application of humic molecules to the leaves led to an increase in the retention of water in the leaves. Additionally, this foliar fertilization bolstered the photosynthetic and antioxidant processes within the plant [100,101]. Applying foliar spray with HA also resulted in increased root length [102]. Research studies have demonstrated that this natural organic substance derived from soil has the potential to

act as a growth regulator for plants. It can effectively modulate hormone levels within plants, leading to improved growth and enhanced tolerance to various environmental stresses such as drought, salinity, and extreme temperatures. HAs are known to have transcriptional interactions with various biochemical components and signaling pathways. Understanding these complex interactions can provide valuable insights into the molecular mechanisms underlying multiple physiological and pathological processes [103]. This natural compound has shown promising results in optimizing crop productivity and overall plant health [104]. In semiarid conditions, applying humic acid to leaves can be an alternative to soil fertilization for providing nitrogen during grain filling in wheat plants [105,106]. The precise involvement of HAs in the molecular mechanism is still not fully understood and requires further investigation and clarification.

7.2. Salinity Stress

Soil salinization adversely impacts crop growth and productivity worldwide, affecting plants in three crucial ways: osmotic, ionic disequilibrium, and cell damage (Table 5). Furthermore, it leads to the accumulation of reactive oxygen species (ROS), impacting protein synthesis, enzymatic activities, and photosynthesis [88].

Therefore, it is essential to comprehend how crops respond to salinity, particularly cereals, to mitigate economic losses, enhance food security, and ensure sustainable agriculture [89]. Globally, wheat is the second most produced cereal crop after maize and rice. Its yield decreases as soil salinity levels rise to 100 mM NaCl [90] and exhibits moderate tolerance to salt stress and experiences significant yield reduction when the salinity level reaches 200 mM [107].

Seaweed extracts represent a rich source of growth-promoting hormones such as IAA and indole-3-butyric acid (IBA), as well as cytokinin. Exposure to salt stress results in a notable decrease in plants' dry weights and shoot length. Moreover, the SE's growth-enhancing potential may be due to the presence of macro and micronutrients [108]. The beneficial stress-relieving effects of seaweed extracts may be connected to cytokinin activity [109]. Additionally, salicylic acid induces the accumulation of auxin and abscisic acid, providing tolerance to salinity stress [110]. The exogenous application of salicylic acid in wheat encourages the production of antioxidants by utilizing ROS as a second messenger [111]. These responses have been shown to decrease oxidative damage under drought, heat, and saline conditions [112]. Mycorrhizal symbiosis helps alleviate salt stress by enhancing soil rhizosphere characteristics, nutrient uptake, water absorption, photosynthetic activity, and the antioxidant system while reducing sodium (Na^+) and chloride (Cl^-) uptake [87]. Similarly, halotolerant endophytic bacteria improved durum wheat performance under saline field conditions, although the response was genotype dependent [113].

Additionally, the use of compost can counteract the detrimental effects of salt stress by enhancing soil fertility, increasing nutrient availability for plants, and stimulating various functions such as respiration, photosynthesis, and the antioxidant system [114].

7.3. Heavy Metal Toxicity

The toxicity of heavy metals has diverse effects on plants, leading to physiological, biochemical, and morphological changes in plants, thereby affecting crop productivity [115,116]. To mitigate the adverse effects of heavy metals, a promising and environmentally friendly approach involves the use of plant biostimulants (Table 5). Chromium becomes toxic to agronomic plants at concentrations of about 0.5 to 5.0 mg mL^{-1} in nutrient solution and 5 to 100 mg g^{-1} in soil. Typically, the concentration of Cr in plants under normal conditions is less than 1 $\mu\text{g g}^{-1}$ [117].

Research by [118] indicated that fulvic acid is widely utilized for removing heavy metals from water.

Previous research has found that cadmium (Cd) in wheat is absorbed through the roots and then transported to the aerial parts, disrupting key metabolic processes that impede normal growth and reproduction [119]. High levels of Cd in the rhizosphere exert severe phytotoxic effects on plant tissues [120], impairing morphological, physiological, and biochemical processes, such as damaging the structure of leaf chlorophyll and deteriorating photosynthetic and gas exchange functions [121,122]. Exogenous application of ascorbic acid (AsA) has been found to increase endogenous production of AsA in wheat tissues, subsequently triggering a robust response to Cd stress. Moreover, the application of AsA to mitigate Cd stress in wheat plants has shown promising benefits, although such studies are limited.

7.4. Temperature

Climate change has become a pressing issue in recent years, posing a significant threat to global food security. Moreover, it is projected that global wheat production will decline by 6% with every one-degree increase in temperature, emphasizing the significance of effective agricultural solutions [123]. Recent research has highlighted the growing concern of terminal heat stress as a significant threat to agriculture mainly due to the impact of climate change [124]. The rise in temperatures has been detrimental to crop growth and yield, leading to accelerated plant development, shortened life cycles, reduced stature, disrupted reproductive cycles, and ultimately decreased yield [125]. Several studies have indicated a positive correlation between the application of fulvic acid and improved wheat yield potential [126] (Table 5).

The unpredictable changes in climate present a significant challenge in meeting the future food needs of a growing population [127]. Agricultural regions worldwide have experienced persistent cold extremes of varying frequency, intensity, and duration, affecting plant growth through mechanical injury and metabolic dysfunction caused by ice crystallization [128,129]. Severe frost damage occurs when the wheat canopy temperature falls 0 °C or below during the spring season [130]. Seaweed extracts play a crucial role as biostimulants, particularly in promoting cold tolerance and preventing cold-stress damage [131]. Although numerous studies suggest that these extracts can enhance cold tolerance [132], scientific research is scarce on the subject. For instance, *A. nodosum* has been utilized in barley [133], tobacco [134], and *Arabidopsis thaliana* (L.) Heynh. [135] to demonstrate their effectiveness. However, the specific mode of action of these products in mitigating cold stress remains unclear despite indications that they enhance membrane integrity and protect chlorophyll. Furthermore, the micronutrients present in seaweed-derived products may also protect against oxidative stress [131]. The significance of biostimulants and their impact on cold-stress responses is substantial, but coherent and comprehensive information on the topic is relatively scarce.

7.5. Nutrient Deficiency

Improving Nutrient use efficiency (NUE) can be attained through enhanced soil management and fertilizer technologies. Plant biostimulants are increasingly being utilized for crop production due to the development of next-generation biostimulants supported by thorough research and a defined mode of action [17] (Table 5). Biostimulants such as AA, SE, and beneficial microbes improve nutrient uptake and assimilation by enhancing root development and microbial symbiosis. These products also stimulate hormonal pathways that optimize nutrient use efficiency, helping plants overcome deficiencies and maintain optimal growth [8]. In this context, a field study on durum wheat showed that soil

inoculation with AMF and PGPR, alone or in combination, enhanced aboveground biomass, nutrient uptake, and the expression of key nitrate, ammonium, and phosphate transporter genes under low-N conditions, highlighting the potential of microbial biostimulants to improve nutrient acquisition efficiency [136]. A further study on durum wheat grown under N-limited, P-rich conditions showed that AMF inoculation significantly increased root colonization and altered root primary metabolism, particularly by reducing free amino acid content in roots, while the combined application of AMF and PGPR partly modified this response, confirming that the effects of microbial biostimulants are strongly influenced by nitrogen availability and soil nutrient context [137].

Phosphate- and potassium-solubilizing bacteria, used together with reduced fertilization and herbicide application, maintained or improved tissue nutrient status and grain yield relative to conventional fertilization, suggesting a potential role in reducing external inputs under field conditions [48].

Together, these findings highlight the broad potential of biostimulants to improve nutrient acquisition efficiency, while also showing that their effects depend on product type, soil fertility, and crop conditions [70,138–142].

Biostimulants extracted from the brown seaweed *A. nodosum* have gained attention for their ability to enhance nutrient use efficiency in various crops [138]; consistently, a three-year field study on winter durum wheat showed that foliar application of *A. nodosum* extract increased grain N accumulation and N-use efficiency, together with grain yield, although responses depended on the growth stage of application and site-year conditions [70]. The biostimulant activity and composition of commercial *A. nodosum* extracts (ANEs) are influenced by the processing conditions of the raw material [139]. Nevertheless, there is limited information explaining the in-depth mechanism of how ANEs promote greater nutrient uptake and assimilation or how the processing parameters of the raw material affect the targeted improvement of NUE in agronomic crops.

Table 5. Effects of biostimulants on wheat under abiotic stresses.

Biostimulants	Effects	Reference
PGPB (<i>Klebsiella</i> sp. SBP-8)	Mitigation of salt stress, Improved wheat growth under salinity, Enhanced antioxidant defense system Improved ion homeostasis (Na ⁺ /K ⁺ balance), Induced systemic tolerance	[77]
Seaweed extract (<i>Sargassum denticulatum</i> Bory)	Enhanced drought tolerance	[135]
PGPR ((<i>Bacillus subtilis</i> Ehrenberg, <i>Arthrobacter protophormiae</i> Lochhead & Burton, and <i>Dietzia natronolimnaea</i> Yoon et al.)	Increased drought tolerance, improved growth and biomass, enhanced photosynthesis, Hormonal and gene regulation under stress	[140]
PGPR (<i>Azospirillum brasilense</i> Tarrand, Krieg & Döbereiner)	Increased biomass, grain yield, nitrogen uptake, and grain protein concentration	[83]
Seaweed Extract (<i>Ulva rigida</i> C. Agardh)	Enhanced salt stress tolerance, Increased chlorophyll and carotenoids, Enhanced antioxidant enzyme activity, Increased phenolic compounds, Reduced oxidative stress, Improved plant physiological performance	[141]

Table 5. Cont.

Biostimulants	Effects	Reference
Humic acid	Enhanced salt stress tolerance, Increased germination and growth, Increased tiller number and grain number, Increased grain weight, Improved yield under salinity stress	[142]
<i>Trichoderma</i> spp.	Enhanced salt stress tolerance, Increased net photosynthesis, Improved water use efficiency, Increased plant growth and biomass, Reduced salinity-induced damage	[107]
Halotolerant endophytic bacteria (<i>Pseudomonas jordanii</i> G34 and <i>Oceanobacillus jordanicus</i> Lee et al. GSFE11)	Alleviation of salinity stress, Improved plant growth and yield under saline conditions, Enhanced biomass and grain production, Improved ion homeostasis (Na^+/K^+ balance), Increased field performance under salt stress	[113]
PGPR (<i>Serratia liquefaciens</i> (Grimes & Hennerty) Bascomb et al., <i>Serratia</i> <i>marcescens</i> Bizio and <i>Bacillus</i> <i>thuringiensis</i> Berliner)	Increased grain yield, Improved wheat quality, Enhanced plant growth, Improved nutrient uptake efficiency, Better overall agronomic performance	[50]
<i>Azotobacter chroococcum</i> Beijerinck and <i>Trichoderma harzianum</i> Rifai (strain 76A and strain T22)	Enhanced tolerance to water and nitrogen deficiency, Improved plant growth and biomass, Increased nitrogen use efficiency, Improved nutrient uptake, Synergistic biostimulant effect (bacteria + fungus)	[44]
Native AMF + <i>Bacillus</i> sp./ <i>Bacillus</i> <i>subtilis</i> Ehrenberg + compost	Improved photosynthetic performance and oxidative stress tolerance under drought stress	[100]
<i>Trichoderma</i> spp.	Alleviation of salt stress in wheat, Improved ion homeostasis (Na^+/K^+ balance), Enhanced osmoregulation, Increased plant growth under salinity, Improved physiological stress tolerance	[53]
PGPR (<i>Enterobacter cloacae</i> Jordan subsp. <i>dissolvens</i> MDSR9)	Enhanced nutrient acquisition (N and P uptake), Increased plant growth and biomass, Improved root development, Enhanced wheat and soybean performance	[46]
Phosphate-solubilizing bacteria and AMF (<i>Pseudomonas fluorescens</i> Migula BAM-4 and <i>Burkholderia cepacia</i> (Burkholder) Yabuuchi et al. BAM-12; <i>Glomus etunicatum</i> (W.N. Becker & Gerd.) C. Walker & A. Schüßler)	Synergistic improvement of growth and yield, Enhanced phosphorus solubilization and uptake, Improved root development, Increased nutrient use efficiency	[74]
Arbuscular mycorrhizal fungi; plant growth-promoting rhizobacteria; AMF + PGPR consortium	Enhanced biomass production Increased nutrient uptake (N and P), Upregulation of N and P transporter genes, Improved plant performance under low-N conditions, Synergistic effect of AMF and PGPR	[136]

7.6. Factors Associated with Variability in Responses

The magnitude, and occasionally the sign, of the wheat response to biostimulants was modulated by three groups of factors. (i) Nitrogen and fertilizer management. Microbial

biostimulants gave their largest relative gains under low or reduced nitrogen, where they partly substituted for mineral fertilizer [37,41,82], whereas seaweed and some formulations improved yield only when nitrogen was co-applied [69,72]. (ii) Water availability and abiotic-stress level. Responses were amplified under drought, salinity and heavy-metal stress (e.g., +43% to +109% under drought) [45]; salinity alleviation [53,77,107]; and chromium tolerance [135], while the same microbial inoculant could impose a transient penalty under non-limiting water and nutrition (−28%) [44]. (iii) Soil fertility and experimental setting. Nutrient-poor, sandy or pot/greenhouse systems produced systematically larger percentage responses than fertile field soils, most clearly shown by the same *Pseudomonas* + P system giving +96% in the greenhouse but +58% in the field [87] and by +92.8% in nutrient-deficient pots [74]. Wheat genotype (ancient vs. modern) [37,86] and product dose (e.g., optimal nanochitin and seaweed concentrations) [76,91] were additional sources of variability. These moderators explain why field responses are typically smaller and more variable than pot responses and argue for interpreting biostimulant efficacy in the context of the target environment and management.

8. Conclusions

The available evidence indicates that biostimulants can improve wheat performance, but their effects are not equally supported across different categories and applications. Among the products reviewed, microbial biostimulants, particularly PGPR and AMF, currently have the strongest and most consistent evidence for enhancing nutrient uptake, increasing grain protein concentration, promoting Zn and Fe accumulation, and supporting wheat performance under nutrient-limited or stress-prone conditions. Their benefits are mainly linked to mechanisms such as biological nitrogen fixation, phosphorus and micronutrient solubilization, phytohormone production, root system enhancement, and improved plant–microbe interactions in the rhizosphere. In contrast, non-microbial biostimulants such as humic substances and seaweed extracts also show positive effects on wheat yield and grain quality, but their efficacy appears to depend more on environmental conditions, formulation, nutrient availability, and application strategy. Emerging approaches, including nano-based products and combined applications with biochar, appear promising under specific stress conditions such as salinity, but the available evidence is still too limited for broad agronomic recommendations.

A major limitation of the current literature is the pronounced heterogeneity in experimental design and reporting standards, including differences in wheat genotype, soil properties, climatic conditions, fertilization regimes, biostimulant composition, dosage, and application timing, which significantly constrains cross-study comparability and the development of generalized recommendations. Future research should prioritize well-designed multi-year and multi-location field trials on both common and durum wheat, adopting standardized reporting of biostimulant formulation, application method, soil fertility status, and environmental conditions, together with harmonized agronomic and physiological indicators such as grain yield, nutrient use efficiency, and grain quality traits. In addition, future studies should systematically evaluate genotype-specific responses and explicitly investigate interactions between biostimulant applications and mineral fertilization regimes, as these factors appear to strongly modulate treatment effectiveness under field conditions. Furthermore, factorial experimental designs and integrative approaches, including multi-omics tools, are recommended to better elucidate mechanisms of action and improve the reproducibility and transferability of results across agroecosystems. Overall, a more mechanistic and systems-based research approach is required to move from predominantly descriptive studies toward reliable, evidence-based recommendations for sustainable wheat production systems. Future research should also place greater emphasis

on biostimulant synergies and their effects on crop quality and resilience, with the aim of improving both productivity and nutritional outcomes in wheat.

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References

1. FAO. *Agricultural Production Statistics—2010–2024*; FAOSTAT Analytical Briefs, No. 121; FAO: Rome, Italy, 2025. [\[CrossRef\]](#)
2. Erenstein, O.; Jaleta, M.; Mottaleb, K.A.; Sonder, K.; Donovan, J.; Braun, H.-J. Global Trends in Wheat Production, Consumption and Trade. In *Wheat Improvement*; Springer International Publishing: Cham, Switzerland, 2022; pp. 47–66.
3. Poole, N.; Donovan, J.; Erenstein, O. Viewpoint: Agri-nutrition research: Revisiting the contribution of maize and wheat to human nutrition and health. *Food Policy* **2021**, *100*, 101976. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Luthria, D.L.; Lu, Y.; John, K.M.M. Bioactive phytochemicals in wheat: Extraction, analysis, processing, and functional properties. *J. Funct. Foods* **2015**, *18*, 910–925. [\[CrossRef\]](#)
5. Zingale, S.; Guarnaccia, P.; Matarazzo, A.; Lagioia, G.; Ingrao, C. A systematic literature review of life cycle assessments in the durum wheat sector. *Sci. Total Environ.* **2022**, *844*, 157230. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Pačuta, V.; Rašovský, M.; Michalska-Klimczak, B.; Wyszynski, Z. Grain yield and quality traits of durum wheat (*Triticum durum* Desf.) treated with seaweed- and humic acid-based biostimulants. *Agronomy* **2021**, *11*, 1270. [\[CrossRef\]](#)
7. Tafuri, A.; Zuccaro, M.; Ravaglia, S.; Pirona, R.; Masci, S.; Sestili, F.; Lafiandra, D.; Ceriotti, A.; Baldoni, E. Exploring variability of free asparagine content in the grain of bread wheat (*Triticum aestivum* L.) varieties cultivated in Italy to reduce acrylamide-forming potential. *Plants* **2023**, *12*, 1349. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Colla, G.; Roupheal, Y.; Bonini, P.; Cardarelli, M. Coating seeds with endophytic fungi enhances growth, nutrient uptake, yield and grain quality of winter wheat. *Int. J. Plant Prod.* **2015**, *9*, 1735–1745.
9. Godfray, H.C.J.; Beddington, J.R.; Crute, I.R.; Haddad, L.; Lawrence, D.; Muir, J.F.; Pretty, J.; Robinson, S.; Thomas, S.M.; Toulmin, C. Food security: The challenge of feeding 9 billion people. *Science* **2010**, *327*, 812–818. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Duma, S.; Shimelis, H.; Tsilo, T.J. Response of bread wheat genotypes for drought and low nitrogen stress tolerance. *Agronomy* **2022**, *12*, 1384. [\[CrossRef\]](#)
11. Bapela, T.; Shimelis, H.; Tsilo, T.J.; Mathew, I. Genetic improvement of wheat for drought tolerance: Progress, challenges and opportunities. *Plants* **2022**, *11*, 1331. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Tilman, D.; Cassman, K.G.; Matson, P.A.; Naylor, R.; Polasky, S. Agricultural sustainability and intensive production practices. *Nature* **2002**, *418*, 671–677. [\[CrossRef\]](#) [\[PubMed\]](#)

13. Adesemoye, A.O.; Torbert, H.A.; Kloepper, J.W. Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. *Microb. Ecol.* **2009**, *58*, 921–929. [[CrossRef](#)] [[PubMed](#)]
14. de Souza, R.; Ambrosini, A.; Passaglia, L.M.P. Plant growth-promoting bacteria as inoculants in agricultural soils. *Genet. Mol. Biol.* **2015**, *38*, 401–419. [[CrossRef](#)] [[PubMed](#)]
15. Dal Cortivo, C.; Conselvan, G.B.; Carletti, P.; Barion, G.; Sella, L.; Vamerali, T. Biostimulant effects of seed-applied sedaxane fungicide: Morphological and physiological changes in maize seedlings. *Front. Plant Sci.* **2017**, *8*, 2072. [[CrossRef](#)] [[PubMed](#)]
16. Di Benedetto, N.A.; Corbo, M.R.; Campaniello, D.; Cataldi, M.P.; Bevilacqua, A.; Sinigaglia, M.; Flagella, Z. The role of plant growth promoting bacteria in improving nitrogen use efficiency for sustainable crop production: A focus on wheat. *AIMS Microbiol.* **2017**, *3*, 413–434. [[CrossRef](#)] [[PubMed](#)]
17. du Jardin, P. Plant biostimulants: Definition, concept, main categories and regulation. *Sci. Hortic.* **2015**, *196*, 3–14. [[CrossRef](#)]
18. Calvo, P.; Nelson, L.; Kloepper, J.W. Agricultural uses of plant biostimulants. *Plant Soil* **2014**, *383*, 3–41. [[CrossRef](#)]
19. Li, J.; Van Gerrewey, T.; Geelen, D. A meta-analysis of biostimulant yield effectiveness in field trials. *Front. Plant Sci.* **2022**, *13*, 836702. [[CrossRef](#)] [[PubMed](#)]
20. Ruzzi, M.; Aroca, R. Plant growth-promoting rhizobacteria act as biostimulants in horticulture. *Sci. Hortic.* **2015**, *196*, 124–134. [[CrossRef](#)]
21. López-Bucio, J.; Pelagio-Flores, R.; Herrera-Estrella, A. *Trichoderma* as biostimulant: Exploiting the multilevel properties of a plant beneficial fungus. *Sci. Hortic.* **2015**, *196*, 109–123. [[CrossRef](#)]
22. Rouphael, Y.; Franken, P.; Schneider, C.; Schwarz, D.; Giovannetti, M.; Agnolucci, M.; De Pascale, S.; Bonini, P.; Colla, G. Arbuscular mycorrhizal fungi act as biostimulants in horticultural crops. *Sci. Hortic.* **2015**, *196*, 91–108. [[CrossRef](#)]
23. Kumar, R.; Barnett-Itzhaki, Z.; Wishkerman, A.; Saha, S.; Sarkar, S.; Roy, A. Reconciling algal growth understanding in photobioreactors through a statistical and facile single parameter (ψ) approach. *Environ. Sci. Adv.* **2025**, *4*, 1650–1662. [[CrossRef](#)]
24. Vo, H.N.P.; Ngo, H.H.; Guo, W.; Nguyen, T.M.H.; Liu, Y.; Liu, Y.; Nguyen, D.D.; Chang, S.W. A critical review on designs and applications of microalgae-based photobioreactors for pollutants treatment. *Sci. Total Environ.* **2019**, *651*, 1549–1568. [[CrossRef](#)] [[PubMed](#)]
25. Backer, R.; Rokem, J.S.; Ilangumaran, G.; Lamont, J.; Praslickova, D.; Ricci, E.; Subramanian, S.; Smith, D.L. Plant growth-promoting rhizobacteria: Context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. *Front. Plant Sci.* **2018**, *9*, 1473. [[CrossRef](#)] [[PubMed](#)]
26. Tarafdar, J.C. Biostimulants for sustainable crop production. In *New and Future Developments in Microbial Biotechnology and Bioengineering*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 299–313.
27. EBIC. *Towards an Optimal Regulatory Framework for Biostimulants*; EBIC: Antwerp, Belgium, 2015. Available online: <https://biostimulants.eu> (accessed on 6 March 2026).
28. EBIC. *Provide Fertile Ground for EU's Continued Leadership in the Biostimulants Industry: EBIC Urges Policy Makers to Adopt the Draft Fertilising Products Regulation*; EBIC: Antwerp, Belgium, 2018. Available online: <https://biostimulants.eu> (accessed on 6 March 2026).
29. Rajabi Hamedani, S.; Rouphael, Y.; Colla, G.; Colantoni, A.; Cardarelli, M. Biostimulants as a tool for improving environmental sustainability of greenhouse vegetable crops. *Sustainability* **2020**, *12*, 5101. [[CrossRef](#)]
30. Barros-Rodríguez, A.; Rangseekaew, P.; Lasudee, K.; Pathom-aree, W.; Manzanera, M. Regulatory risks associated with bacteria as biostimulants and biofertilizers in the frame of the European Regulation (EU) 2019/1009. *Sci. Total Environ.* **2020**, *740*, 140239. [[CrossRef](#)] [[PubMed](#)]
31. Hendriksen, N.B. Microbial biostimulants—the need for clarification in EU regulation. *Trends Microbiol.* **2022**, *30*, 311–313. [[CrossRef](#)] [[PubMed](#)]
32. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [[CrossRef](#)] [[PubMed](#)]
33. Singh, J.S.; Pandey, V.C.; Singh, D.P. Efficient soil microorganisms: A new dimension for sustainable agriculture and environmental development. *Agric. Ecosyst. Environ.* **2011**, *140*, 339–353. [[CrossRef](#)]
34. Ayed, S.; Bouhaouel, I.; Jebari, H.; Hamada, W. Use of Biostimulants: Towards Sustainable Approach to Enhance Durum Wheat Performances. *Plants* **2022**, *11*, 133. [[CrossRef](#)] [[PubMed](#)]
35. Gorim, L.; Asch, F. Effects of composition and share of seed coatings on the mobilization efficiency of cereal seeds during germination. *J. Agron. Crop Sci.* **2012**, *198*, 81–91.
36. Foulkes, M.J.; Hawkesford, M.J.; Barraclough, P.B.; Holdsworth, M.J.; Kerr, S.; Kightley, S.; Shewry, P.R. Identifying traits to improve the nitrogen economy of wheat: Recent advances and future prospects. *Field Crops Res.* **2009**, *114*, 329–342. [[CrossRef](#)]
37. Pagnani, G.; Galieni, A.; Stagnari, F.; Pellegrini, M.; Del Gallo, M.; Pisante, M. Open field inoculation with PGPR as a strategy to manage fertilization of ancient *Triticum* genotypes. *Biol. Fertil. Soils* **2020**, *56*, 111–124.

38. Pérez-Montaña, F.; Alías-Villegas, C.; Bellogín, R.A.; del Cerro, P.; Espuny, M.R.; Jiménez-Guerrero, I.; López-Baena, F.J.; Ollero, F.J.; Cubo, T. Plant growth promotion in cereal and leguminous agricultural important plants: From microorganism capacities to crop production. *Microbiol. Res.* **2014**, *169*, 325–336. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Nelson, D.R.; Mele, P.M. The impact of crop residue amendments and lime on microbial community structure and nitrogen-fixing bacteria in the wheat rhizosphere. *Soil Res.* **2006**, *44*, 319–329. [\[CrossRef\]](#)
40. Behl, R.K.; Ruppel, S.; Kothe, E.; Neeru Narula, N.N. Wheat $\times$ *Azotobacter* $\times$ VA Mycorrhiza interactions towards plant nutrition and growth—a review. *J. Appl. Bot. Food Qual.* **2007**, *81*, 95–109.
41. Neiverth, A.; Delai, S.; Garcia, D.M.; Saatkamp, K.; de Souza, E.M.; de Oliveira Pedrosa, F.; Guimarães, V.F.; dos Santos, M.F.; Vendruscolo, E.C.G.; da Costa, A.C.T. Performance of different wheat genotypes inoculated with the plant growth promoting bacterium *Herbaspirillum seropedicae*. *Eur. J. Soil Biol.* **2014**, *64*, 1–5. [\[CrossRef\]](#)
42. Ayala Zepeda, M.; Valenzuela Ruiz, V.; Parra Cota, F.I.; Chinchilla-Soto, C.; de la Cruz Torres, E.; Ibba, M.I.; Estrada Alvarado, M.I.; de los Santos Villalobos, S. Genomic insights of a native bacterial consortium for wheat production sustainability. *Curr. Res. Microb. Sci.* **2024**, *6*, 100230. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Ayala-Zepeda, M.; Parra-Cota, F.I.; Chinchilla-Soto, C.; De La Cruz-Torres, E.; Ibba, M.I.; Estrada-Alvarado, M.I.; de los Santos-Villalobos, S. ¹⁵N-Nitrogen use efficiency, productivity, and quality of durum wheat integrating nitrogen management and an indigenous bacterial inoculant in a single growing season. *Appl. Sci.* **2025**, *15*, 1429. [\[CrossRef\]](#)
44. Silletti, S.; Di Stasio, E.; Van Oosten, M.J.; Ventorino, V.; Pepe, O.; Napolitano, M.; Marra, R.; Woo, S.L.; Cirillo, V.; Maggio, A. Biostimulant activity of *Azotobacter chroococcum* and *Trichoderma harzianum* in durum wheat under water and nitrogen deficiency. *Agronomy* **2021**, *11*, 380. [\[CrossRef\]](#)
45. Roy, B.; Raghavendra, N.; Gupta, N.; Nigohjkar, A. Isolation of plant growth-promoting microorganisms and their impact on growth and yield of durum wheat. *Appl. Biochem. Microbiol.* **2024**, *60*, 315–330. [\[CrossRef\]](#)
46. Ramesh, A.; Sharma, S.K.; Sharma, M.P.; Yadav, N.; Joshi, O.P. Plant growth-promoting traits in *Enterobacter cloacae* subsp. *dissolvens* MDSR9 isolated from soybean rhizosphere and its impact on growth and nutrition of soybean and wheat upon inoculation. *Agric. Res.* **2014**, *3*, 53–66. [\[CrossRef\]](#)
47. Bechtaoui, N.; Raklami, A.; Tahiri, A.I.; Benidire, L.; El Alaoui, A.; Meddich, A.; Göttfert, M.; Oufdou, K. Characterization of plant growth promoting rhizobacteria and their benefits on growth and phosphate nutrition of faba bean and wheat. *Biol. Open* **2019**, *8*, bio043968. [\[PubMed\]](#)
48. Gazoulis, I.; Zannopoulos, S.; Kokkini, M.; Antonopoulos, N.; Kanatas, P.; Kanetsi, M.; Demirtzoglou, T.; Travlos, I. A Preliminary Assessment of the Combined Effects of a Novel Microbial Biostimulant Product, Fertilizers, and Herbicides on the Growth and Yield of Field Crops in Greece. *Agronomy* **2014**, *14*, 1636.
49. Chami, B.; Touzout, N.; Guemouri-Athmani, S.; Baali-Cherif, D.; Mihoub, A.; Černý, J.; Saeed, M.F.; Jamal, A.; Yassine, H.M.; Dewir, Y.H.; et al. Bacterial Inoculation and Co-Inoculation Improves Durum Wheat Productivity in Alkaline Calcareous Soils. *Phyton* **2024**, *93*, 3313–3328. [\[CrossRef\]](#)
50. Abaid-Ullah, M.; Hassan, M.N.; Jamil, M.; Brader, G.; Kausar, M.; Shah, N.; Sessitsch, A.; Hafeez, F.Y. Plant growth promoting rhizobacteria: An alternate way to improve yield and quality of wheat (*Triticum aestivum*). *Int. J. Agric. Biol.* **2015**, *17*, 51–60.
51. Parađiković, N.; Vinkovic, T.; Vrček, I.V.; Tkalec, M. Natural biostimulants reduce the incidence of BER in sweet yellow pepper plants (*Capsicum annuum* L.). *Agric. Food Sci.* **2013**, *22*, 307–317. [\[CrossRef\]](#)
52. Abdolmaleki, A.K.; Pirdashti, H.; Yaghoubian, Y.; Abbasian, A.; Shiade, S.R.G. Endophytic fungi improve growth and yield of wheat (*Triticum aestivum* L.) under limited light conditions. *Gesunde Pflanz.* **2023**, *75*, 1517–1529.
53. Bouzouina, M.; Kouadria, R.; Lotmani, B. Fungal endophytes alleviate salt stress in wheat in terms of growth, ion homeostasis and osmoregulation. *J. Appl. Microbiol.* **2021**, *130*, 913–925. [\[PubMed\]](#)
54. Yun, P.; Xu, L.; Wang, S.-S.; Shabala, L.; Shabala, S.; Zhang, W.-Y. *Piriformospora indica* improves salinity stress tolerance in *Zea mays* L. plants by regulating Na⁺ and K⁺ loading in root and allocating K⁺ in shoot. *Plant Growth Regul.* **2018**, *86*, 323–331. [\[CrossRef\]](#)
55. Gill, S.S.; Gill, R.; Trivedi, D.K.; Anjum, N.A.; Sharma, K.K.; Ansari, M.W.; Ansari, A.A.; Johri, A.K.; Prasad, R.; Pereira, E.; et al. *Piriformospora indica*: Potential and significance in plant stress tolerance. *Front. Microbiol.* **2016**, *7*, 332. [\[CrossRef\]](#) [\[PubMed\]](#)
56. Sharma, P.; Patel, A.N.; Saini, M.K.; Deep, S. Field demonstration of *Trichoderma harzianum* as a plant growth promoter in wheat (*Triticum aestivum* L.). *J. Agric. Sci.* **2012**, *4*, 65–73. [\[CrossRef\]](#)
57. Sobhani, S.M.A.; Alavifazel, M.; Ardakani, M.R.; Modhej, A.; Lak, S. Influence of mycorrhizal fungi and biochar on nitrogen use efficiency correlated with yield and yield components of wheat. *Plant Sci. Today* **2022**, *9*, 1486.
58. Pellegrino, E.; Öpik, M.; Bonari, E.; Ercoli, L. Responses of wheat to arbuscular mycorrhizal fungi: A meta-analysis of field studies from 1975 to 2013. *Soil Biol. Biochem.* **2015**, *84*, 210–217. [\[CrossRef\]](#)
59. Shabani, G.; Ardakani, M.R.; Chaichi, M.R.; Friedel, J.K.; Khavazi, K. Effect of different fertilizing treatments on nutrient uptake in annual medic (*Medicago scutellata* Cv. Robinson) under irrigated and dry farming systems. *J. Agric. Sci. Technol.* **2015**, *17*, 1735–1745.

60. Silva, P.S.T.; Cassiolato, A.M.R.; Galindo, F.S.; Jalal, A.; Nogueira, T.A.R.; da Silva Oliveira, C.E.; Filho, M.C.M.T. *Azospirillum brasilense* and zinc rates effect on fungal root colonization and yield of wheat-maize in tropical savannah conditions. *Plants* **2022**, *11*, 3154. [[CrossRef](#)] [[PubMed](#)]
61. Raklami, A.; Bechtaoui, N.; Tahiri, A.; Anli, M.; Meddich, A.; Oufdou, K. Use of Rhizobacteria and Mycorrhizae Consortium in the Open Field as a Strategy for Improving Crop Nutrition, Productivity and Soil Fertility. *Front. Microbiol.* **2019**, *10*, 1106. [[CrossRef](#)] [[PubMed](#)]
62. Khan, R.U.; Khan, M.Z.; Khan, A.; Saba, S.; Hussain, F.; Jan, I.U. Effect of humic acid on growth and crop nutrient status of wheat on two different soils. *J. Plant Nutr.* **2018**, *41*, 453–460. [[CrossRef](#)]
63. Dinçsoy, M.; Sönmez, F. The effect of potassium and humic acid applications on yield and nutrient contents of wheat (*Triticum aestivum* L. var. Delfii) with same soil properties. *J. Plant Nutr.* **2019**, *42*, 2757–2772. [[CrossRef](#)]
64. Delfine, S.; Tognetti, R.; Desiderio, E.; Alvino, A. Effect of foliar application of N and humic acids on growth and yield of durum wheat. *Agron. Sustain. Dev.* **2005**, *25*, 183–191. [[CrossRef](#)]
65. Mutlu, A.; Tas, T. Foliar application of humic acid at heading improves physiological and agronomic characteristics of durum wheat (*Triticum durum* L.). *J. King Saud Univ. Sci.* **2022**, *34*, 102320. [[CrossRef](#)]
66. Shah, M.T.; Zodape, S.T.; Chaudhary, D.R.; Eswaran, K.; Chikara, J. Seaweed sap as an alternative liquid fertilizer for yield and quality improvement of wheat. *J. Plant Nutr.* **2013**, *36*, 192–200. [[CrossRef](#)]
67. Moreno-Moraga, A.; Sánchez-Rodríguez, A.R.; González-Sánchez, E.J.; Márquez-García, F. Use of Amino Acids and Slow-Release Urea-Based Biostimulants to Enhance Yield and Grain Quality in Durum Wheat Under No-Tillage Conditions in Semi-Arid Region. *Agronomy* **2025**, *15*, 2150. [[CrossRef](#)]
68. Mahmoud, S.H.; Salama, D.M.; El-Tanahy, A.M.M.; El-Samad, E.H.A. Utilization of seaweed (*Sargassum vulgare*) extract to enhance growth, yield and nutritional quality of red radish plants. *Ann. Agric. Sci.* **2019**, *64*, 167–175. [[CrossRef](#)]
69. Stamatiadis, S.; Evangelou, L.; Yvin, J.-C.; Tsadilas, C.; Mina, J.M.G.; Cruz, F. Responses of winter wheat to *Ascophyllum nodosum* (L.) Le Jol. extract application under the effect of N fertilization and water supply. *J. Appl. Phycol.* **2015**, *27*, 589–600. [[CrossRef](#)] [[PubMed](#)]
70. Stamatiadis, S.; Evangelou, E.; Jamois, F.; Yvin, J.C. Targeting *Ascophyllum nodosum* (L.) Le Jol. extract application at five growth stages of winter wheat. *J. Appl. Phycol.* **2021**, *33*, 1873–1882. [[CrossRef](#)]
71. Soliman, M.H.; Alnusairi, G.S.H.; Khan, A.A.; Alnusaire, T.S.; Fakhr, M.A.; Abdulmajeed, A.M.; Aldesuquy, H.S.; Yahya, M.; Najeeb, U. Biochar and selenium nanoparticles induce water transporter genes for sustaining carbon assimilation and grain production in salt-stressed wheat. *J. Plant Growth Regul.* **2023**, *42*, 1522–1543.
72. Maignan, V.; Bernay, B.; Géliot, P.; Avicé, J.-C. Biostimulant effects of Glutacetine® and its derived formulations mixed with N fertilizer on post-heading N uptake and remobilization, seed yield, and grain quality in winter wheat. *Front. Plant Sci.* **2020**, *11*, 607615. [[CrossRef](#)] [[PubMed](#)]
73. Popko, M.; Michalak, I.; Wilk, R.; Gramza, M.; Chojnacka, K.; Górecki, H. Effect of the new plant growth biostimulants based on amino acids on yield and grain quality of winter wheat. *Molecules* **2018**, *23*, 470. [[CrossRef](#)] [[PubMed](#)]
74. Minaxi; Saxena, J.; Chandra, S.; Nain, L. Synergistic effect of phosphate solubilizing rhizobacteria and arbuscular mycorrhiza on growth and yield of wheat plants. *J. Soil Sci. Plant Nutr.* **2013**, *13*, 511–522. [[CrossRef](#)]
75. Mathur, N.; Vyas, A. Influence of arbuscular mycorrhizae on biomass production, nutrient uptake and physiological changes in *Ziziphus mauritiana* Lam. under water stress. *J. Arid Environ.* **2000**, *45*, 191–195. [[CrossRef](#)]
76. Mukherjee, S.; Rice, M.S.; Zimba, C. Effect of *Kappaphycus alvarezii* (Doty) Doty ex Silva extract on grain quality, yield and some yield components of wheat (*Triticum aestivum* L.). *Int. J. Plant Prod.* **2009**, *3*, 115–125. [[CrossRef](#)]
77. Singh, R.P.; Jha, P.; Jha, P.N. The plant-growth-promoting bacterium *Klebsiella* sp. SBP-8 confers induced systemic tolerance in wheat (*Triticum aestivum*) under salt stress. *J. Plant Physiol.* **2015**, *184*, 57–67. [[CrossRef](#)] [[PubMed](#)]
78. Mackowiak, C.L.; Grossl, P.R.; Bugbee, B.G. Beneficial effects of humic acid on micronutrient availability to wheat. *Soil Sci. Soc. Am. J.* **2001**, *65*, 1744–1750. [[CrossRef](#)] [[PubMed](#)]
79. Rossini, A.; Ruggeri, R.; Rossini, F. Use of Foliar Biostimulants in Durum Wheat: Understanding Its Potential in Improving Agronomic and Quality Responses Under Mediterranean Field Conditions. *Plants* **2025**, *14*, 2276. [[CrossRef](#)] [[PubMed](#)]
80. Laurent, E.A.; Ahmed, N.; Durieu, C.; Grief, P.; Lamaze, T. Marine and fungal biostimulants improve grain yield, nitrogen absorption and allocation in durum wheat plants. *J. Agric. Sci.* **2020**, *158*, 279–287. [[CrossRef](#)]
81. Rossini, A.; Ruggeri, R.; Rossini, F. Combining nitrogen fertilization and biostimulant application in durum wheat: Effects on morphophysiological traits, grain production, and quality. *Ital. J. Agron.* **2025**, *20*, 100027. [[CrossRef](#)]
82. Çakmakçı, R.; Turan, M.; Güllüce, M.; Şahin, F. Rhizobacteria for reduced fertilizer inputs in wheat (*Triticum aestivum* spp. vulgare) and barley (*Hordeum vulgare*) on Aridisols in Turkey. *Int. J. Plant Prod.* **2014**, *8*, 1735–1745. [[CrossRef](#)]
83. Saubidet, M.I.; Fatta, N.; Barneix, A.J. The effect of inoculation with *Azospirillum brasilense* on growth and nitrogen utilization by wheat plants. *Plant Soil* **2002**, *245*, 215–222. [[CrossRef](#)]

84. Mäder, P.; Kaiser, F.; Adholeya, A.; Singh, R.; Uppal, H.S.; Sharma, A.K.; Srivastava, R.; Sahai, V.; Aragno, M.; Wiemken, A.; et al. Inoculation of root microorganisms for sustainable wheat–rice and wheat–black gram rotations in India. *Soil Biol. Biochem.* **2011**, *43*, 609–619. [\[CrossRef\]](#)
85. Roesti, D.; Gaur, R.; Johri, B.; Imfeld, G.; Sharma, S.; Kawaljeet, K.; Aragno, M. Plant growth stage, fertiliser management and bio-inoculation of arbuscular mycorrhizal fungi and plant growth promoting rhizobacteria affect the rhizobacterial community structure in rain-fed wheat fields. *Soil Biol. Biochem.* **2006**, *38*, 1111–1120. [\[CrossRef\]](#)
86. Ercoli, L.; Schüßler, A.; Arduini, I.; Pellegrino, E. Strong increase of durum wheat iron and zinc content by field-inoculation with arbuscular mycorrhizal fungi at different soil nitrogen availabilities. *Plant Soil* **2017**, *419*, 153–167. [\[CrossRef\]](#)
87. Zabihi, H.R.; Savaghebi, G.R.; Khavazi, K.; Ganjali, A.; Miransari, M. Pseudomonas bacteria and phosphorous fertilization, affecting wheat (*Triticum aestivum* L.) yield and P uptake under greenhouse and field conditions. *Acta Physiol. Plant* **2011**, *33*, 145–152. [\[CrossRef\]](#)
88. Ait-El-Mokhtar, M.; Baslam, M.; Ben-Laouane, R.; Anli, M.; Boutasknit, A.; Mitsui, T.; Wahbi, S.; Meddich, A. Alleviation of detrimental effects of salt stress on date palm (*Phoenix dactylifera* L.) by the application of arbuscular mycorrhizal fungi and/or compost. *Front. Sustain. Food Syst.* **2020**, *4*, 131. [\[CrossRef\]](#)
89. Mukhopadhyay, R.; Sarkar, B.; Jat, H.S.; Sharma, P.C.; Bolan, N.S. Soil salinity under climate change: Challenges for sustainable agriculture and food security. *J. Environ. Manag.* **2021**, *280*, 111736. [\[CrossRef\]](#) [\[PubMed\]](#)
90. Nguyen, V.L.; Stangoulis, J. Salt tolerance in wheat is associated with the maintenance of shoot biomass, stomatal conductance, and sucrose in the phloem. *Plant-Environ. Interact.* **2024**, *5*, e70008. [\[CrossRef\]](#) [\[PubMed\]](#)
91. Xue, W.; Han, Y.; Tan, J.; Wang, Y.; Wang, G.; Wang, H. Effects of nanochitin on the enhancement of the grain yield and quality of winter wheat. *J. Agric. Food Chem.* **2018**, *66*, 6637–6645. [\[CrossRef\]](#) [\[PubMed\]](#)
92. Nasiroleslami, E.; Mozafari, H.; Sadeghi-Shoei, M.; Habibi, D.; Sani, B. Changes in yield, protein, minerals, and fatty acid profile of wheat (*Triticum aestivum* L.) under fertilizer management involving application of nitrogen, humic acid, and seaweed extract. *J. Soil Sci. Plant Nutr.* **2021**, *21*, 2642–2651. [\[CrossRef\]](#)
93. Lephatsi, M.; Nephali, L.; Meyer, V.; Piater, L.A.; Buthelezi, N.; Dubery, I.A.; Opperman, H.; Brand, M.; Huyser, J.; Tugizimana, F. Molecular mechanisms associated with microbial biostimulant-mediated growth enhancement, priming and drought stress tolerance in maize plants. *Sci. Rep.* **2022**, *12*, 10450. [\[CrossRef\]](#) [\[PubMed\]](#)
94. Sunita, K.; Mishra, I.; Mishra, J.; Prakash, J.; Arora, N.K. Secondary metabolites from halotolerant plant growth promoting rhizobacteria for ameliorating salinity stress in plants. *Front. Microbiol.* **2020**, *11*, 567768. [\[CrossRef\]](#) [\[PubMed\]](#)
95. Hasanuzzaman, M.; Parvin, K.; Bardhan, K.; Nahar, K.; Anee, T.I.; Masud, A.A.C.; Fotopoulos, V. Biostimulants for the regulation of reactive oxygen species metabolism in plants under abiotic stress. *Cells* **2021**, *10*, 2537. [\[CrossRef\]](#) [\[PubMed\]](#)
96. Mrid, R.B.; Benmrid, B.; Hafsa, J.; Boukcim, H.; Sobeh, M.; Yasri, A. Secondary metabolites as biostimulant and bioprotectant agents: A review. *Sci. Total Environ.* **2021**, *777*, 146204. [\[CrossRef\]](#)
97. Nephali, L.; Piater, L.A.; Dubery, I.A.; Patterson, V.; Huyser, J.; Burgess, K.; Tugizimana, F. Biostimulants for plant growth and mitigation of abiotic stresses: A metabolomics perspective. *Metabolites* **2020**, *10*, 505. [\[CrossRef\]](#) [\[PubMed\]](#)
98. Rouphael, Y.; Colla, G. Synergistic biostimulatory action: Designing the next generation of plant biostimulants for sustainable agriculture. *Front. Plant Sci.* **2018**, *9*, 1655. [\[PubMed\]](#)
99. Nezhadahmadi, A.; Prodhan, Z.H.; Faruq, G. Drought tolerance in wheat. *Sci. World J.* **2013**, *2013*, 610721. [\[CrossRef\]](#) [\[PubMed\]](#)
100. Ikan, C.; Soussani, F.E.; Ouhammadou, R.; Ech-Chatir, L.; Errouh, F.; Boutasknit, A.; Assouguem, A.; Ali, E.A.; Ullah, R.; Ait Barka, E.; et al. Use of Biofertilizers as an Effective Management Strategy to Improve the Photosynthetic Apparatus, Yield, and Tolerance to Drought Stress of Drip-Irrigated Wheat in Semi-Arid Environments. *Agronomy* **2024**, *14*, 1316. [\[CrossRef\]](#)
101. Nabi, F.; Sarfaraz, A.; Kama, R.; Kanwal, R.; Li, H. Structure-based function of humic acid in abiotic stress alleviation in plants: A review. *Plants* **2025**, *14*, 1916. [\[CrossRef\]](#) [\[PubMed\]](#)
102. Tahoun, A.M.A.; El-Enin, M.M.A.; Mancy, A.G.; Sheta, M.H.; Shaaban, A. Integrative soil application of humic acid and foliar plant growth stimulants improves soil properties and wheat yield and quality in nutrient-poor sandy soil of a semiarid region. *J. Soil Sci. Plant Nutr.* **2022**, *22*, 2857–2871. [\[CrossRef\]](#) [\[PubMed\]](#)
103. García, A.C.; Olaetxea, M.; Santos, L.A.; Mora, V.; Baigorri, R.; Fuentes, M.; Zamarreño, A.M.; Berbara, R.L.L.; Garcia-Mina, J.M. Involvement of hormone- and ROS-signaling pathways in the beneficial action of humic substances on plants growing under normal and stressing conditions. *BioMed Res. Int.* **2016**, *2016*, 3747501. [\[CrossRef\]](#) [\[PubMed\]](#)
104. Ma, Y.; Cheng, X.; Zhang, Y. The impact of humic acid fertilizers on crop yield and nitrogen use efficiency: A meta-analysis. *Agronomy* **2024**, *14*, 2763. [\[CrossRef\]](#)
105. Johnson, R.R.; Frey, N.M.; Moss, D.N. Effect of water stress on photosynthesis and transpiration of flag leaves and spikes of barley and wheat. *Crop Sci.* **1974**, *14*, 728–731. [\[CrossRef\]](#)
106. Mousavi, S.M.; Tadayon, M.S.; Far, J.S. Integrated application of foliar biostimulants and biofertilizers improves wheat resilience, nutrient uptake, and yield under deficit irrigation in semi-arid regions. *Agric. Water Manag.* **2025**, *322*, 109958. [\[CrossRef\]](#)

107. Oljira, A.M.; Hussain, T.; Waghmode, T.R.; Zhao, H.; Sun, H.; Liu, X.; Wang, X.; Liu, B. *Trichoderma* enhances net photosynthesis, water use efficiency, and growth of wheat (*Triticum aestivum* L.) under salt stress. *Microorganisms* **2020**, *8*, 1565. [[CrossRef](#)] [[PubMed](#)]
108. Nuruzzaman, M.; Tahjib-Ul-Arif, M.; Hannan, M.A.; Murata, Y.; Hossain, M.A. Seaweed Extracts Improve Salinity Tolerance in Cereal Crops—A Meta-Analysis. *Plant-Environ. Interact.* **2025**, *6*, e70094. [[CrossRef](#)] [[PubMed](#)]
109. Pise, N.M.; Sabale, A.B. Effect of seaweed concentrates on the growth and biochemical constituents of *Trigonella foenum-graecum* L. *J. Phytol.* **2010**, *2*, 50–56.
110. Shakirova, F.M.; Avalbaev, A.M.; Bezrukova, M.V.; Fatkhutdinova, R.A.; Maslennikova, D.R.; Yuldashev, R.A.; Allagulova, C.R.; Lastochkina, O.V. Hormonal intermediates in the protective action of exogenous phytohormones in wheat plants under salinity. In *Phytohormones and Abiotic Stress Tolerance in Plants*; Springer: Berlin/Heidelberg, Germany, 2012; pp. 185–228.
111. Agarwal, S.; Sairam, R.K.; Srivastava, G.C.; Meena, R.C. Changes in antioxidant enzymes activity and oxidative stress by abscisic acid and salicylic acid in wheat genotypes. *Biol. Plant.* **2005**, *49*, 541–550. [[CrossRef](#)]
112. Fardus, J.; Matin, M.A.; Hasanuzzaman, M.; Hossain, M.S.; Nath, S.D.; Hossain, M.A.; Rohman, M.M.; Hasanuzzaman, M. Exogenous salicylic acid-mediated physiological responses and improvement in yield by modulating antioxidant defense system of wheat under salinity. *Not. Sci. Biol.* **2017**, *9*, 219–232. [[CrossRef](#)]
113. Albdaawi, R.; Al-Sayaydeh, R.; Al-Rifaei, M.K.; Alhindi, T.; Ashraf, M.; Al-Abdallat, A.M. Halotolerant Endophytic Bacteria Regulate Growth and Field Performance of Two Durum Wheat Genotypes with Contrasting Salinity Tolerance Potential. *Plants* **2024**, *13*, 1179. [[CrossRef](#)] [[PubMed](#)]
114. Mbarki, S.; Labidi, N.; Talbi, O.; Jdidi, N.; Abdelli, C.; Pascual, J.A. Ameliorative effect of municipal solid waste compost on the biological quality of Mediterranean salt lake soil. *Compost Sci. Util.* **2010**, *18*, 242–248. [[CrossRef](#)]
115. Shahid, M.; Dumat, C.; Silvestre, J.; Pinelli, E. Effect of fulvic acids on lead-induced oxidative stress to metal sensitive *Vicia faba* L. plant. *Biol. Fertil. Soils* **2012**, *48*, 689–697. [[CrossRef](#)]
116. Guo, S.; Shen, G.Q.; Peng, Y. Embodied agricultural water use in China from 1997 to 2010. *J. Clean. Prod.* **2016**, *112*, 3176–3184. [[CrossRef](#)]
117. Oliveira, H. Chromium as an environmental pollutant: Insights on induced plant toxicity. *J. Bot.* **2012**, *2012*, 375843. [[CrossRef](#)]
118. Tang, W.W.; Zeng, G.M.; Gong, J.L.; Liang, J.; Xu, P.; Zhang, C.; Huang, B.B. Impact of humic/fulvic acid on the removal of heavy metals from aqueous solutions using nanomaterials: A review. *Sci. Total Environ.* **2014**, *468–469*, 1014–1027. [[CrossRef](#)] [[PubMed](#)]
119. Abedi, T.; Mojiri, A. Cadmium uptake by wheat (*Triticum aestivum* L.): An overview. *Plants* **2020**, *9*, 500. [[CrossRef](#)] [[PubMed](#)]
120. Riaz, M.; Kamran, M.; El-Esawi, M.A.; Hussain, S.; Wang, X. Boron-toxicity induced changes in cell wall components, boron forms, and antioxidant defense system in rice seedlings. *Ecotoxicol. Environ. Saf.* **2021**, *216*, 112192. [[CrossRef](#)] [[PubMed](#)]
121. Santos, C.L.V.; Campos, A.; Azevedo, H.; Caldeira, G. In situ and in vitro senescence induced by KCl stress: Nutritional imbalance, lipid peroxidation and antioxidant metabolism. *J. Exp. Bot.* **2001**, *52*, 351–360. [[CrossRef](#)]
122. Malik, A.; Mor, V.S.; Tokas, J.; Punia, H.; Malik, S.; Malik, K.; Sangwan, S.; Tomar, S.; Singh, P.; Singh, N.; et al. Biostimulant-treated seedlings under sustainable agriculture: A global perspective facing climate change. *Agronomy* **2020**, *11*, 14. [[CrossRef](#)]
123. Asseng, S.; Ewert, F.; Martre, P.; Rötter, R.P.; Lobell, D.B.; Cammarano, D.; Kimball, B.A.; Ottman, M.J.; Wall, G.W.; White, J.W.; et al. Rising temperatures reduce global wheat production. *Nat. Clim. Chang.* **2015**, *5*, 143–147. [[CrossRef](#)]
124. Nagar, S.; Singh, V.P.; Arora, A.; Dhakar, R.; Ramakrishnan, S. Assessment of terminal heat tolerance ability of wheat genotypes based on physiological traits using multivariate analysis. *Acta Physiol. Plant.* **2015**, *37*, 257. [[CrossRef](#)]
125. Hatfield, J.L.; Prueger, J.H. Temperature extremes: Effect on plant growth and development. *Weather Clim. Extrem.* **2015**, *10*, 4–10. [[CrossRef](#)]
126. Van Oosten, M.J.; Pepe, O.; De Pascale, S.; Silletti, S.; Maggio, A. The role of biostimulants and bioeffectors as alleviators of abiotic stress in crop plants. *Chem. Biol. Technol. Agric.* **2017**, *4*, 5. [[CrossRef](#)]
127. Röder, M.; Thornley, P.; Campbell, G.; Bows-Larkin, A. Emissions associated with meeting the future global wheat demand: A case study of UK production under climate change constraints. *Environ. Sci. Policy* **2014**, *39*, 13–24. [[CrossRef](#)]
128. Yadav, S.K. Cold stress tolerance mechanisms in plants. A review. *Agron. Sustain. Dev.* **2010**, *30*, 515–527. [[CrossRef](#)]
129. Kodra, E.; Steinhäuser, K.; Ganguly, A.R. Persisting cold extremes under 21st-century warming scenarios. *Geophys. Res. Lett.* **2011**, *38*, L08705. [[CrossRef](#)]
130. Frederiks, T.M.; Christopher, J.T.; Sutherland, M.W.; Borrell, A.K. Post-head-emergence frost in wheat and barley: Defining the problem, assessing the damage, and identifying resistance. *J. Exp. Bot.* **2015**, *66*, 3487–3498. [[CrossRef](#)] [[PubMed](#)]
131. Digruher, T.; Sass, L.; Cseri, A.; Paul, K.; Nagy, A.V.; Remenyik, J.; Molnár, I.; Vass, I.; Toldi, O.; Gyuricza, C.; et al. Stimulation of energy willow biomass with triacontanol and seaweed extract. *Ind. Crops Prod.* **2018**, *120*, 104–112. [[CrossRef](#)]
132. Burchett, M.D.; Pulkownik, A.; Grant, C.; Macfarlane, G. Rehabilitation of saline wetlands, Olympics 2000 site, Sydney (Australia)—I: Management strategies based on ecological needs assessment. *Mar. Pollut. Bull.* **1999**, *37*, 515–525. [[CrossRef](#)]

133. Zamani-Babgohari, M.; Critchley, A.T.; Norrie, J.; Prithiviraj, B. Increased freezing stress tolerance of *Nicotiana tabacum* L. cv. Bright Yellow-2 cell cultures with the medium addition of *Ascophyllum nodosum* (L.) Le Jolis extract. *Vitr. Cell. Dev. Biol. Plant* **2019**, *55*, 321–333. [[CrossRef](#)]
134. Rayirath, P.; Benkel, B.; Hodges, D.M.; Allan-Wojtas, P.; MacKinnon, S.; Critchley, A.T.; Prithiviraj, B. Lipophilic components of the brown seaweed, *Ascophyllum nodosum*, enhance freezing tolerance in *Arabidopsis thaliana*. *Planta* **2009**, *230*, 135–147. [[CrossRef](#)] [[PubMed](#)]
135. Ali, A.H.; Said, E.M.; Abdelgawad, Z.A. The role of seaweed extract on improvement drought tolerance of wheat revealed by osmoprotectants and DNA (cpDNA) markers. *Braz. J. Bot.* **2022**, *45*, 857–867. [[CrossRef](#)]
136. Saia, S.; Rappa, V.; Ruisi, P.; Abenavoli, M.R.; Sunseri, F.; Giambalvo, D.; Frenda, A.S.; Martinelli, F. Soil inoculation with symbiotic microorganisms promotes plant growth and nutrient transporter genes expression in durum wheat. *Front. Plant Sci.* **2015**, *6*, 815. [[CrossRef](#)] [[PubMed](#)]
137. Saia, S.; Ruisi, P.; Fileccia, V.; Di Miceli, G.; Amato, G.; Martinelli, F. Metabolomics Suggests That Soil Inoculation with Arbuscular Mycorrhizal Fungi Decreased Free Amino Acid Content in Roots of Durum Wheat Grown under N-Limited, P-Rich Field Conditions. *PLoS ONE* **2015**, *10*, e0129591. [[CrossRef](#)] [[PubMed](#)]
138. Goñi, O.; Quille, P.; O’Connell, S. *Ascophyllum nodosum* extract biostimulants and their role in enhancing tolerance to drought stress in tomato plants. *Plant Physiol. Biochem.* **2018**, *126*, 63–73. [[CrossRef](#)] [[PubMed](#)]
139. Shaikh, S.; Saraf, M. Biofortification of *Triticum aestivum* through the inoculation of zinc solubilizing plant growth promoting rhizobacteria in field experiment. *Biocatal. Agric. Biotechnol.* **2017**, *9*, 120–126. [[CrossRef](#)]
140. Barnawal, D.; Bharti, N.; Pandey, S.S.; Pandey, A.; Chanotiya, C.S.; Kalra, A. Plant growth-promoting rhizobacteria enhance wheat salt and drought stress tolerance by altering endogenous phytohormone levels and TaCTR1/TaDREB2 expression. *Physiol. Plant.* **2017**, *161*, 502–514. [[CrossRef](#)] [[PubMed](#)]
141. Chernane, H.; Latique, S.; Mansori, M.; El Kaoua, M. Salt stress tolerance and antioxidative mechanisms in wheat plants (*Triticum durum* L.) by seaweed extracts application. *J. Agric. Vet. Sci.* **2015**, *8*, 36–44.
142. Shah, S.M.O.; Jamal, Y.; Haq, I.U. Effect of Humic acid on Wheat (*Triticum aestivum* L.) under saline conditions. *Pure Appl. Biol.* **2023**, *13*, 93–100. [[CrossRef](#)]

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