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Systematic Review

Role of Biostimulants in Sustainable Soybean (*Glycine max* L.) Production: A Systematic Review

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Abstract

This systematic review critically evaluates and synthesizes current evidence on the efficacy of biostimulants in enhancing soybean seed yield and quality. A comprehensive literature search was conducted following the PRISMA approach using the Web of Science (WoS) database, focusing on peer-reviewed studies from 2014 to 2025 reporting on the effects of biostimulants applied alone or in combination with other agro-inputs on soybean performance. Over 500 publications were retrieved from the database, of which 72 were included in this review. Extracted data were used to calculate changes in yield (kg ha^{-1}), percentage yield increase (%), oil content (%), and protein concentration (%). Our synthesis demonstrated that the sole application of biostimulants, including seaweed extracts, humic acids, amino acids, and beneficial microbes (*Bradyrhizobium*, PGPR, AMF), consistently enhanced soybean yield by 4% to 65%, while their interaction with other agro-inputs was shown to be capable of increasing yield by more than 150% under abiotic stress conditions, indicating strong synergistic effects. These improvements are mediated through various physiological mechanisms such as enhanced nutrient uptake, improved root growth, increased photosynthetic efficiency, and elevated stress tolerance. Furthermore, biostimulant application positively affects seed quality, increasing oil and protein content by 0.4–5.5% and 0.5–7.3%, respectively, by optimizing source–sink relationships and metabolic pathways. Overall, the greatest benefits are frequently observed through synergistic combinations of biostimulants with one another or with reduced rates of mineral fertilizers, highlighting a promising pathway toward sustainable crop intensification in soybean systems.

Keywords: soybean seed yield; seed quality; humic acid; seaweed extract; plant-growth-promoting rhizobacteria (PGPR); arbuscular mycorrhizal fungi (AMF); sustainable intensification

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Academic Editors: Agnieszka Szparaga, Nedjoud Grara, Mahmood Ahmed and Sana Besnaci

Received: 1 December 2025
Revised: 2 January 2026
Accepted: 5 January 2026
Published: 8 January 2026

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1. Introduction

Soybean is an important oilseed crop known for its nitrogen-fixing ability and is cultivated globally for both feed and food. The global production of soybeans in 2024 reached 427.14 million metric tons [1]. It is considered the most important source of vegetable oil and protein because its seeds contain approximately 20% oil and 40% protein,

respectively [2]. These quality traits make soybeans a valuable raw material for manufacturing various products, including biofuels and edible oils [3]. Despite its worldwide importance, soybean production is constrained by several factors, including abiotic stresses such as water deficit, soil salinity, soil compaction, soil degradation, and declining soil fertility in particular [4–6]. These stresses can severely reduce productivity, contributing to 50–70% yield losses in global crop production [7,8]. In addition, traditional agricultural practices relying heavily on synthetic fertilizers and pesticides, while effective in enhancing yields, also lead to long-term negative impacts on soil health, biodiversity, and ecosystem stability [9–11], including soil and water pollution and greenhouse gas emissions [10,12,13]. This underscores the growing need for sustainable alternatives that maintain productivity while preserving soil health and ecological balance.

Biostimulants have emerged as a promising agroecological innovation to enhance crop resilience, productivity, and quality under diverse environmental conditions. Biostimulant has become a general term for plant-beneficial substances that are neither nutrients, pesticides, nor soil improvers. Du Jardin et al. [14] defined biostimulants as microorganisms or natural substances of plant or microbial origin capable of improving abiotic stress tolerance, nutrient use efficiency, and crop quality independently of direct nutrient supply. These substances or microbes represent a paradigm shift from direct nutrient supplementation to the modulation of plant physiological processes. Biostimulants can be broadly classified into non-microbial groups, such as humic acids, seaweed extracts, amino acids, and fulvic acids, and microbial biostimulants, including plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), phosphate-solubilizing bacteria, and *Trichoderma* spp. [15–17].

The mechanisms through which biostimulants act are multifaceted and often synergistic. Their functions include improving nutrient assimilation, stimulating root development, modulating hormone signaling pathways, and enhancing plant resilience against unfavorable climatic conditions [15,16,18–23]. Considering the high nutrient demand and stress sensitivity of soybeans, integrating biostimulants into soybean production systems could provide substantial agronomic benefits.

Non-microbial biostimulants such as humic acids improve soil structure, water retention, and root membrane permeability [24]. They also promote microbial colonization, enhance nutrient chelation, and exhibit hormone-like activities that improve nutrient use efficiency (NUE). Amino acids enhance nutrient transport, act as micronutrient chelators, and serve as precursors for hormonal and stress-related metabolic pathways, contributing to improved stomatal regulation and reduced oxidative stress. For instance, Zanin et al. [25] demonstrated that humic acids bind essential nutrients in the soil, increasing their bioavailability, while Matuszak-Slamani et al. [26] reported that humic acid significantly boosts soybeans' resilience to abiotic stresses. Similarly, seaweed extracts are rich in phytohormones and bioactive compounds that stimulate plant defense responses [27] and promote cell division and elongation, resulting in vigorous soybean growth [28–31]. Furthermore, the combined application of humic acids and seaweed extracts increases soybean oil and protein content [32] as well as stimulating the synthesis of secondary metabolites [33].

Microbial biostimulants, also known as biofertilizers, leverage symbiotic or associative interactions to enhance nutrient uptake and crop productivity [34–37]. These microbes colonize the rhizosphere, fix atmospheric nitrogen, solubilize nutrients, and produce auxin-like compounds [38,39]. For example, *Trichoderma* spp. enhance root expansion and induce systemic resistance [40]. Phosphate-solubilizing microorganisms (PSM) release organic acids and enzymes that convert unavailable phosphorus into plant-available forms, improving phosphorus efficiency and reducing dependence on synthetic fertilizers [41]. Likewise, PGPR promote plant growth by producing phytohormones, mobilizing micronutrients, and

improving stress tolerance [42,43]. In soybean, inoculation with *Bradyrhizobium japonicum* significantly increases nitrogen uptake and yield [44–46]. Co-inoculation with *Bacillus* strains and AMF, especially when combined with phosphate fertilizers, results in substantial increases in soybean yield and profitability, representing a promising sustainable agricultural strategy [47]. Collectively, these mechanisms highlight the strength of symbiotic relationships as long-term strategies for improving crop productivity and mitigating climate change-related stresses.

Despite the promising benefits of biostimulants, challenges remain in optimizing their use. Studies have highlighted the difficulties in standardizing application methods, understanding environmental interactions, and predicting consistent outcomes across cultivars and agroecological zones [48–50]. Variability in experimental designs, environmental conditions, and soybean genotypes across studies complicates consistent interpretation of results [19,51]. Moreover, most existing research has focused on specific products, individual treatments, particular plant stress conditions (for example, abiotic stresses such as drought, salinity, nutrient imbalance, or extreme temperature), or application methods, leaving a gap in the comprehensive synthesis of their agronomic potential. Therefore, we hypothesize that the strategic application of natural plant-derived substances and beneficial microbial biostimulants, alone or in combination, can significantly enhance both nutritional quality and yield of soybean under diverse environmental conditions. By critically evaluating the current literature, this systematic review aims to synthesize the existing evidence on the efficacy of biostimulants in improving soybean yield and quality traits, identify key knowledge gaps, and propose optimized biostimulant strategies for sustainable soybean production.

2. Materials and Methods

2.1. Strategy for Document Search and Identification and Criteria for Exclusion and Inclusion

A comprehensive literature search was conducted in accordance with the PRISMA 2020 guidelines [52] to identify articles and studies relevant to the subject of this review. All stages of the review process, including study identification, screening, eligibility assessment, data extraction, and synthesis, followed the PRISMA framework, and a complete PRISMA checklist is provided in the Supplementary Materials. Before the initial search, we acknowledged that scientific literature is widely available across multiple databases, including Web of Science (WoS), PubMed, Scopus, and Google Scholar. Among these, the Web of Science database—containing approximately 34,000 indexed journals—was selected by the review authors because it is one of the most reliable, well-established, and widely used sources of peer-reviewed research and citations worldwide [53].

The search was performed on November 2025 using the following keywords: (“biostimulant*” OR “phytostimulant*” OR “biofertiliser*” OR “microorganism*” OR “humic acid*” OR “fulvic acid” OR “seaweed extract*”) AND (“Soybean” OR “Glycine max”) AND (“yield” OR “productivity” OR “grain quality”). Manual screening and evaluation were conducted based on the titles and abstracts of retrieved articles to determine their relevance to the topic under investigation.

Following the initial screening, a more detailed assessment of the selected articles was carried out. Studies were included only if they met the following criteria: (i) original research articles and (ii) reporting the effects of biostimulants on soybean seed yield and/or seed quality. Details of the inclusion and exclusion process are presented in Table 1, and an overview of the literature search strategy following the PRISMA 2020 guidelines is shown in Figure 1.

Table 1. Criteria for document exclusion and inclusion.

Decision	Steps	Description
Excluded	I	Articles that provide limited or insufficient information on biostimulants, even if soybean is used as the test crop
Excluded	II	Articles that do not report data on soybean seed yield or quality but instead evaluate biostimulant effects on other crops.
Excluded	III	Articles that mention both biostimulants and soybean but lack quantitative or measurable evidence of effects.
Excluded	IV	Articles in which biostimulants were applied in combination with other agro-inputs or biofertilizers, without isolating or reporting the sole or interaction effects of biostimulants on soybean seed yield and quality.
Included	V	Only articles that met all inclusion criteria and did not fall under exclusions I–IV were selected for systematic evaluation

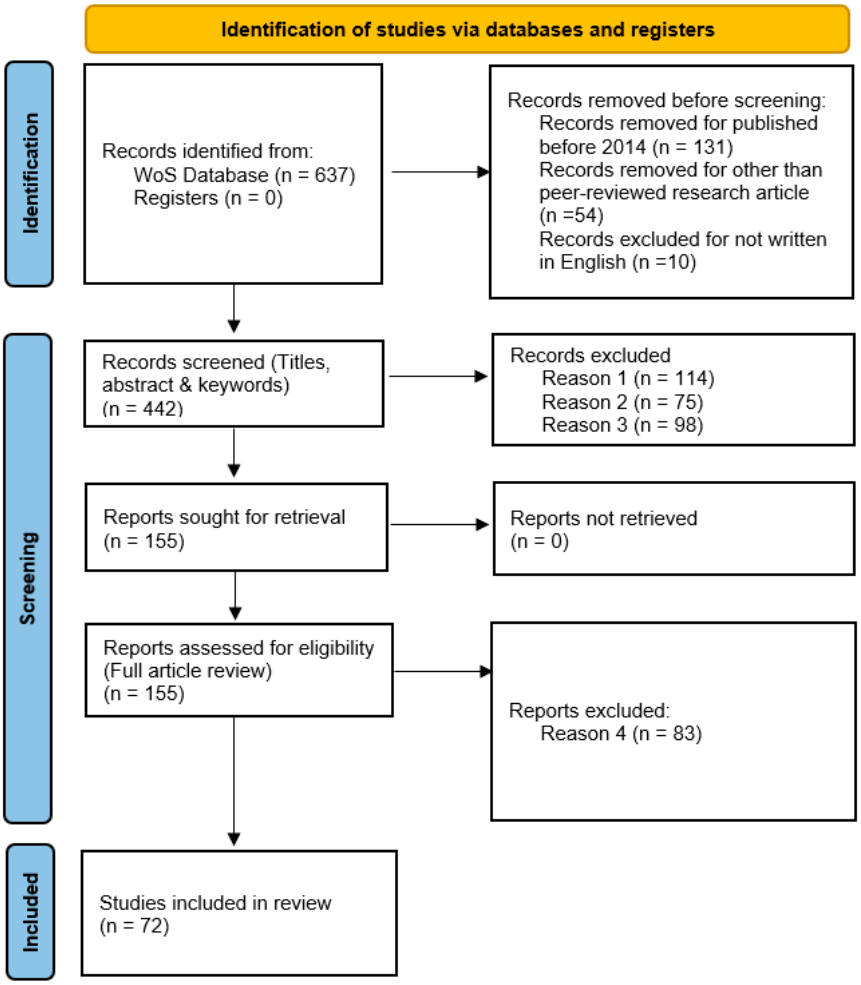


Figure 1. The PRISMA flow diagram. Reason 1: Articles that provide limited or insufficient information on biostimulants, even if soybean is used as the test crop. Reason 2: Articles that do not report data on soybean seed yield or quality but instead evaluate biostimulant effects on other crops. Reason 3: Articles that mention both biostimulants and soybean but lack quantitative or measurable evidence of effects. Reason 4: Articles in which biostimulants were applied in combination with other agro-inputs or biofertilizers, without isolating or reporting the sole or interaction effects of biostimulants on soybean seed yield and quality.

2.2. Data Extraction, Analysis, Preparation, and Synthesis Procedure

Following full-text screening, included studies were independently examined, and data were categorized by outcome domains (seed yield, protein content, and oil content) and study characteristics, including biostimulant type and formulation. Data extraction was performed by a single reviewer using a predefined and standardized data extraction form. Extracted information comprised publication details, biostimulant type, soil type, mode of application, application rate, experimental location, and reported outcome measures (seed yield, protein, and oil content). Where seed yield or quality data were presented exclusively in graphical format, numerical values were extracted using WebPlotDigitizer 5.2 software [54]. Changes in seed yield were calculated and subsequently expressed as percentage values [55–57] to enable standardized and uniform descriptive reporting. When yield was reported in g plant^{-1}, values were converted to kg ha^{-1} using the following equation: yield (kg ha^{-1}) = (g plant^{-1} × plant density)/1000. A standard plant density of 250,000 plants ha^{-1} was assumed when the density was not reported in the original article.

Study characteristics and outcome data from individual studies were summarized in tabular form to facilitate qualitative comparison and narrative synthesis. Due to substantial heterogeneity in study designs, biostimulant formulations, and outcome measures, quantitative synthesis (meta-analysis) was not conducted. Instead, findings were synthesized qualitatively using structured descriptive and comparative approaches to identify trends, inconsistencies, and contextual factors influencing outcomes. Consistent with PRISMA recommendations for narrative synthesis, formal assessments of statistical heterogeneity, subgroup analyses, sensitivity analyses, reporting bias evaluation, and grading of evidence certainty were not performed, as no quantitative data pooling or statistical modeling was undertaken.

3. Results and Discussion

3.1. Geographical Scope of Included Literature

The literature search and selection process followed a systematic protocol to ensure a comprehensive and relevant review. The initial search identified a total of 637 publications in the Web of Science (WoS) database. To focus on the most recent and relevant research, the results were filtered to include publications from 2014 to 2025, narrowing the pool to 506 publications. This set was further refined to include only peer-reviewed journal articles written in English, resulting in 442 publications.

These 442 articles then underwent a critical screening process, during which their abstracts—and, when necessary, full texts—were evaluated for their direct relevance to the objectives of this study. Based on this rigorous assessment, 72 publications met the inclusion criteria.

The distribution of publications across years showed a gradual increase from 2014 to 2025. The year 2025 recorded the highest number of publications, contributing to 19.4% of the total, followed by 2024 with 15.3%. Both 2022 and 2023 produced 10 publications each, representing 13.9% of the total. In contrast, 2014, 2015, and 2016 each produced only one publication (1.4% of the total) (Figure 2).

Geographically, the included studies originated primarily from South America, which accounted for 36 articles (50%), followed by Europe and Asia with 16 each (22.2%), and Africa and North America with 2 each (2.8%) (Figure 3). The higher number of publications from South America may be attributed to its dominant role in global soybean production, the prevalence of region-specific stress conditions, and strong agricultural research networks. Additionally, to enhance research output in regions with fewer publications,

investments in research infrastructure, international collaborations, and locally conducted field trials are essential.

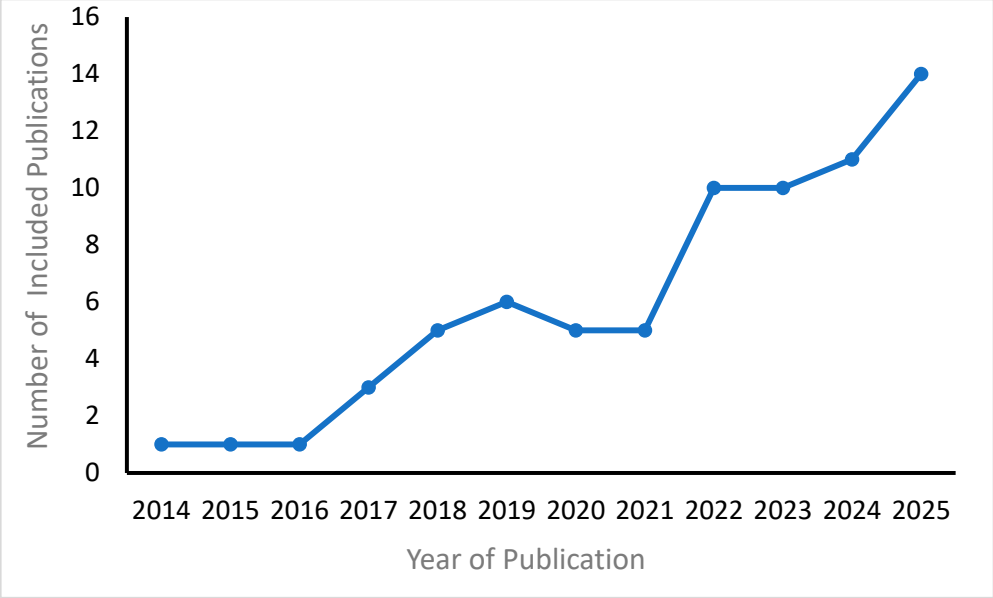


Figure 2. Number of publications included in the systematic review from 2014 to 2025.

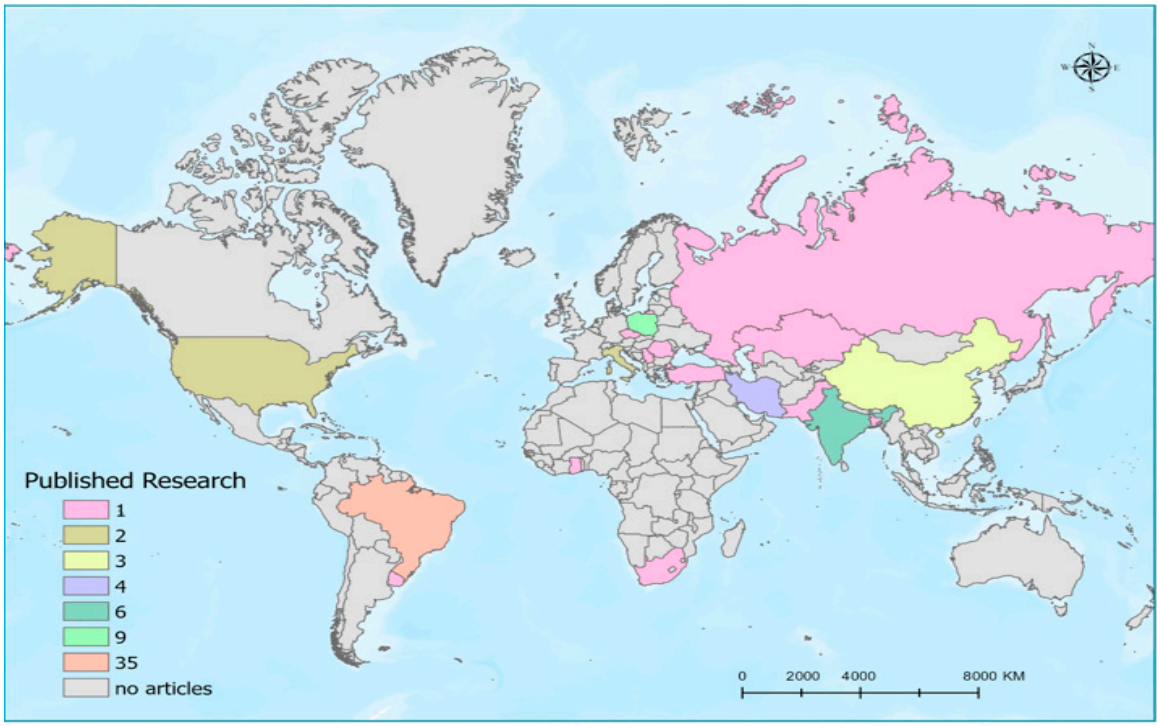


Figure 3. Publication distribution by country.

3.2. Effect of Humic Acid and Amino Acids on Soybean Seed Yield

Evaluating the application of humic acids and amino acids as main effects reveals a notable enhancement in soybean yield across various application methods compared with the control (Table S1). Khan et al. [32] reported that foliar application of humic acids resulted in a seed yield of 3576 kg ha^{-1}, representing a 23.2% increase over the control yield of 2901 kg ha^{-1}. Miraezami et al. [58] similarly found that foliar application of humic acid improved seed yield by 65.1% (2750 kg ha^{-1}) compared with the control (1667 kg ha^{-1}). Lenssen et al. [59] also observed that foliar humic acid application increased yield by

16.93% (1091 kg ha^{-1}) compared with the control (933 kg ha^{-1}), whereas Franzoni et al. [60] reported a 9.3% increase (5441 kg ha^{-1}) compared with the untreated plot (4979 kg ha^{-1}). Collectively, these studies clearly demonstrate that humic acids consistently exert positive effects on soybean productivity, primarily by enhancing nutrient uptake efficiency and mitigating abiotic stress such as drought, salinity, and temperature extremes.

Overall, our evaluation indicates that humic acids can increase soybean seed yield by 9–65%, highlighting their substantial biostimulatory potential. The benefits are particularly evident when applied as foliar treatments, as they not only improve yield but can also enhance economic returns and seed quality [59]. These enhancements are linked to the ability of humic acids to improve soil health and directly stimulate plant physiology. They increase cation exchange capacity, enhance root architecture, and stimulate microbial activity in the rhizosphere. This microbial stimulation promotes carbon assimilation, providing the energy required for nitrogen fixation and, ultimately, improving nutrient uptake and photosynthetic performance [61,62]. Mechanistically, humic substances also exhibit auxin-like hormonal activity, which promotes lateral root development and optimizes nutrient transport to aerial tissues, thereby enhancing morphological development and final yield.

Amino acids have also been shown to significantly improve soybean yield. As building blocks of proteins and precursors to vital biomolecules, amino acids function as signaling molecules that activate stress–response pathways. Da Silva et al. [4], who tested 17 different biostimulants (including amino acids and algae extract) via foliar application under typical yellow Oxisol soil conditions, found that serine, betaine, glycine, and arginine were the most effective, producing yields of 5075 kg ha^{-1}, 4679 kg ha^{-1}, and 4547 kg ha^{-1}, representing increases of 47.8%, 36.3%, and 32.4% compared with the control (3434 kg ha^{-1}). Kocira [33] similarly reported that two foliar applications of amino acids at a 5% concentration increased yield by 39% (4095 kg ha^{-1}) compared with the control (3064 kg ha^{-1}). Franzoni et al. [60] found that foliar application of vegetal amino acids and animal-derived amino acids (enzymatic or chemical extraction) at 3 mL L^{-1} increased yield by 9.5% (5464 kg ha^{-1}), 5.3% (5245 ha^{-1}), and 8.8% (5418 kg ha^{-1}), respectively, compared with the untreated plot (4979 kg ha^{-1}). In a tropical Oxisol, Bagateli et al. [63] reported that foliar-applied germinate increased yield by 8.64% (4334 kg ha^{-1}) compared with the control yield of 3990 kg ha^{-1}. In another study, Costa et al. [64] achieved an even greater enhancement by treating seeds with clove essential oil, resulting in a yield of 5114 kg ha^{-1}, a 17.2% increase relative to the control yield of 4365 kg ha^{-1}.

These findings reveal that amino acids also possess significant biostimulant potential, with soybean yield gains ranging from 5.3% to 47.8%. Particularly strong effects were observed with specific amino acids like serine, glycine, and arginine. Variability in response can be attributed to amino acid type, origin, concentration, and timing of application. Mechanisms include improved osmotic adjustment, activation of antioxidant defenses, and stimulation of root growth for enhanced water and nutrient uptake [65–68]. Additionally, amino acids may act as molecular signals that activate transcription factors regulating cell division, hormonal pathways, and resource allocation, thus enhancing plant productivity under both optimal and stress conditions.

Comparative analysis shows that the maximum yield improvement recorded under foliar humic acid application (65.1%) exceeds the highest improvement reported for amino acids (47.8%). This suggests that although both biostimulants are effective, humic acids may provide a broader spectrum of benefits—particularly under challenging edaphic conditions—due to their direct impact on soil health. In contrast, amino acids appear to act more directly on plant physiology, making them highly valuable for the rapid correction of metabolic constraints during vegetative growth. Foliar application emerges as the most

effective delivery method for both humic acids and amino acids, enabling direct absorption and rapid plant response.

To optimize their agronomic potential, future research should focus on identifying synergistic combinations of these biostimulants under diverse environmental conditions. Furthermore, molecular-level investigations into their effects on gene expression, enzyme activity, and metabolomic profiles would provide deeper insight into the regulatory networks they influence, supporting the development of more precise application strategies.

3.3. Effect of Seaweed Extracts on Soybean Seed Yield

Seaweed extract is one of the most extensively studied categories of biostimulants. In this study, we evaluated trials in which seaweed extracts and seaweed-derived products were applied across various soil types. The critically assessed findings are presented in Table S2. Seaweed extracts emerged as some of the most widely investigated biostimulants, with consistent evidence demonstrating their capacity to improve the soybean seed yield across soil types and management practices. For example, Khan et al. [32] found that seaweed extract applied at 24 kg ha^{-1} increased yield by 14.1% (3319 kg ha^{-1}) compared with the control yield of 2901 kg ha^{-1} under typical silt loam soil. Mannan et al. [6] examined different concentrations of seaweed extract in sandy loam soil and reported that 10% (*v*/*v*) application improved yield by 23.6% (126 kg ha^{-1}) over the untreated plots (102 kg ha^{-1}). A similar study by Arab et al. [69] in Iran under silt loam conditions revealed that seaweed extract applied at 0.3% increased yield by 36.6% (2730 kg ha^{-1}) compared with the control of 1998 kg ha^{-1}.

Szparaga et al. [70] observed a yield of 3318 kg ha^{-1} (a 39.3% increase) compared with 2382 kg ha^{-1} following the application of macerates, a biostimulant derived from Levisticum roots, applied at 30 kg ha^{-1} per 300 L of water. Kocira [33] noted a substantial yield improvement of 4169 kg ha^{-1} (36.1%) compared with the control (3064 kg ha^{-1}) when kelp-derived phytohormones were applied at higher concentrations. Krawczuk et al. [71] similarly demonstrated that seaweed extract applied at 1.0% per 300 L ha^{-1} via API 2003 increased yield by 31.4% (3512 kg ha^{-1}) over the control yield of 2673 kg ha^{-1}. Pavlova et al. [72] also reported that potassium humate and the product Vostok EM increased yield by 19.7% (2670 kg ha^{-1}) and 12.5% (2510 kg ha^{-1}) compared with the control (2230 kg ha^{-1}). Collectively, these findings demonstrate consistent yield increases across soil types, highlighting the robust agronomic value of seaweed extracts in soybean production. These benefits may stem from humic substances improving soil structure and water retention, thereby enhancing nutrient availability and creating more favorable growth conditions.

The biostimulant action of seaweed extracts—primarily derived from species such as *Ascophyllum nodosum* and *Ecklonia maxima*—is multifaceted. These extracts are rich in bioactive compounds, including betaines, polysaccharides, and hormone-like substances (such as cytokinins, auxins) [73]. These components act synergistically to enhance plant performance. Under favorable conditions, they improve photosynthetic efficiency and modulate source–sink dynamics, encouraging greater assimilate allocation toward reproductive structures [74]. For example, Franzoni et al. [60] examined seaweed products derived from *Ascophyllum nodosum* and *Ecklonia maxima*, each applied at 3 mL L^{-1} in silt loam soil, and reported yield increases of 10.9% (5522 kg ha^{-1}) and 9.3% (5441 kg ha^{-1}), respectively, compared with the control (4979 kg ha^{-1}). Similarly, Sirbu et al. [75] reported a 27.0% increase in yield (1880 kg ha^{-1}) with *Ascophyllum nodosum* extract (FERT A) at 2.5 L ha^{-1} under albic luvisol soil compared with the control (1480 kg ha^{-1}). Langowski et al. [76] reported yield improvements of 4.0–9.9% with SealicitTM (A. nodosum) under red clay latosol, increasing yield from 3522 kg ha^{-1} to 3666–3874 kg ha^{-1}. Meyer et al. [77] found that Booster® seaweed extract (*Ecklonia maxima*) applied at different rates increased yield

by 3–5% (5234–5346 kg ha^{-1}) compared with the control (5079 kg ha^{-1}). In temperate silt loam soil in Poland, Gaweda et al. [78] identified Kelpak SL as the most effective treatment, increasing yield by 11.3% (3350 kg ha^{-1}), outperforming other treatments like Asahi (8.6%) and Aminoplant (5.3%) compared with the control (3010 kg ha^{-1}). Under semiarid conditions, Jesus et al. [79] observed a 3.16% yield increase (2402 kg ha^{-1}) with *Ascophyllum nodosum* compared with the control (2329.1 kg ha^{-1}). Collectively, these studies highlight the ability of seaweed extracts—particularly those from *Ascophyllum nodosum* and *Ecklonia maxima*—to enhance antioxidant activity, nutrient uptake, and tolerance to abiotic stress, ultimately improving soybean productivity.

Beyond yield enhancement under optimal conditions, seaweed-based biostimulants also play a crucial role in stress resilience. Several studies report substantial yield protection under drought and heat stress, with yield increases of up to 54.8% (1544.4 kg ha^{-1}) under water-deficit conditions compared with the control yield of 997 kg ha^{-1} [6]. This protective effect is linked to the upregulation of antioxidant defense systems, increased accumulation of osmoprotectants such as proline, and improved membrane stability [33,79]. Additionally, polysaccharides in seaweed extracts can enhance soil moisture retention and stimulate beneficial microbial activity, further contributing to stress resilience. The magnitude of the yield response depends on factors such as the seaweed species, extraction method, application rate, and timing.

Taken together, the evidence strongly supports the assertion that biostimulants derived from seaweed extracts and seaweed-based products consistently improve soybean seed yield across soil types, environmental conditions, and application strategies. Our synthesis reveals a yield improvement range of 4.0–54.8%, with particularly strong benefits under abiotic stress. These improvements are likely driven by enhanced nutrient uptake, improved stress tolerance, hormone-mediated growth regulation, and the stimulation of beneficial soil microbial activity. Despite growing evidence supporting the effectiveness of seaweed extracts—particularly in enhancing physiological resilience and nutrient use efficiency—their adoption remains limited in many regions. Future research should focus on characterizing dose–response relationships for specific soybean cultivars and environmental conditions. Additionally, exploring synergistic interactions between seaweed extracts and other biostimulants, such as microbial inoculants, may further enhance sustainable yield gains.

3.4. Effect of Beneficial Microbes on Soybean Seed Yield

Beneficial bacteria and fungi classified as biostimulants have been extensively studied for their potential to enhance crop productivity. As shown in Table S3, their efficacy varies considerably depending on the application method (seed, soil, and foliar), microbial strain, and environmental conditions; however, they consistently demonstrate positive effects on soybean. A critical but often overlooked factor contributing to this variability is the soybean genotype, which can significantly influence microbial colonization and functional efficiency.

In the context of seed inoculation, numerous studies have demonstrated that single-strain inoculation with Rhizobium or *Bradyrhizobium japonicum* enhances yield by improving nodulation and biological nitrogen fixation (BNF). For instance, Miraezami et al. [58] evaluated the effectiveness of Rhizobium via seed inoculation and reported a 33.6% yield increase (1721 kg ha^{-1}) compared with the control (1288 kg ha^{-1}). Similarly, Khan et al. [32] observed a yield of 3552 kg ha^{-1} in inoculated seeds compared with 3309 kg ha^{-1} in the control, representing a 7.3% yield improvement. These improvements can be attributed to enhanced early establishment, increased N fixation, and greater nodule efficiency. How-

ever, the genetic compatibility between the host plant and microbial strain remains a key determinant of inoculation success.

Gatabazi et al. [44] tested three levels of peat- and liquid-formulated *Bradyrhizobium japonicum* strain WB74 in sandy loam soil. They reported yield increases of 30.6% (1741 kg ha^{-1}) with peat formulation and 29.7% (1724 kg ha^{-1}) with liquid formulation compared to the control (1330 kg ha^{-1}). Although both formulations improved soybean yield, efficacy declined at higher dosages, indicating the importance of optimal inoculant concentration. Hatipoğlu and Haliloğlu [80] also reported an 18.7% yield increase (3645 kg ha^{-1}) following seed inoculation with *B. japonicum* compared with 3072 kg ha^{-1} in the control. Conversely, Souza et al. [81] observed only a minor yield increase (0.5%), with *B. japonicum* via seed treatment, potentially due to the already high yield level in the control (6390 vs. 6420 kg ha^{-1}).

However, not all studies demonstrated yield gains. Travençoli Rossetim et al. [82] found that individual inoculation with *Bradyrhizobium* in a typic dystrohumic Cambisol resulted yield decrease of 4.5–16.5% relative to the control (3920 kg ha^{-1}). Such reductions may be linked to nutrient imbalances, poor microbial compatibility, or unfavorable climatic conditions disrupting symbiosis. Colet et al. [83] similarly attributed poor yield responses to competition between inoculant strains and native soil microorganisms, or insufficient conditions for effective plant-microbe interaction.

Nonetheless, Avornyo et al. [84] recorded a 30.4% increase (2310 kg ha^{-1}) following Rhizobium inoculation compared with the control (1772 kg ha^{-1}), reinforcing the potential of microbial biostimulants. These findings highlight that although Rhizobium inoculation is generally effective, its success is highly dependent on application method, dosage, and soil conditions. Moreover, the compatibility between rhizobial strain and the soybean genotype can significantly modulate nitrogen fixation efficiency, leading to strain–cultivar specificity.

Beyond seed inoculation, Vishwanatha et al. [85] reported that foliar application of Rhizobium plus phosphate-solubilising bacteria (PSB) at 1.25 kg increased yield by 12.2% (1431 kg ha^{-1}) compared with the control (1275 kg ha^{-1}). Yield improvements in soybean are largely attributed to enhanced nutrient availability, particularly through potassium and phosphorus solubilization, which promotes overall plant growth and productivity [86]. Biological nitrogen fixation remains a critical driver of productivity, especially in nutrient-poor soils [87].

Taken together, these studies indicate that Rhizobium and *Bradyrhizobium* inoculants reliably improve soybean yield, typically within the range of 7.0–33.6%. Their effectiveness stems from enhanced nodulation, nitrogen fixation, and early plant vigor. However, excessive inoculant dosage can reduce efficacy, underscoring the need for optimized application strategies.

In contrast, co-inoculation with complementary plant growth-promoting rhizobacteria (PGPR) often produces greater yield benefits than single inoculants, although the outcomes may vary depending on microbial compatibility. This variability is further influenced by the host plant genotype, which affects the root exudate profile and the associated microbial community. Marinkovic et al. [88] explored the potential of co-inoculating a PGPR strain with a microbiological fertilizer through seed treatment to enhance soybean productivity. Their findings showed that co-inoculation of *Bradyrhizobium japonicum* with Azotobacter chroococcum increased yield by 9.0% (4588 kg ha^{-1}), outperforming single *Bradyrhizobium japonicum* treatments and other combinations with *Bacillus subtilis*, as well as the control yield of 4208 kg ha^{-1}. Garcia et al. [89] also evaluated peat- and liquid-based *Bradyrhizobium* spp. strains SEMIA 5077 + SEMIA 5080 via seed treatment on Latossol Vermelho Distrófico soil and reported a yield gain of 99.6% (3796 kg ha^{-1}) under

composite inoculation (*B. japonicum* + *Azospirillum brasilense*), compared to the control of 1902 kg ha^{-1}. Similarly, Queiroz Rego et al. [90] observed a 40.08% yield improvement (4079 kg ha^{-1}) when seeds were co-inoculated with *B. japonicum* + *A. brasilense* (250 mL + 250 mL), compared with 2912 kg ha^{-1} in the control plots. Marchão et al. [91] reported a 6.2% yield increase (3810 kg ha^{-1}) using a combination of *Pseudomonas fluorescens* and *A. brasilense*, which surpassed the yield gains achieved by individual treatments and the control yield (3585 kg ha^{-1}).

Bomfim et al. [92] revealed that seed inoculation with specific strains (SI + ME-LCO) increased yield by 17.1%. Likewise, De-Lima et al. [93] reported that nicotinamide at 200 mg L^{-1} increased yield by 15.4% (4510 kg ha^{-1}) over the control (3962 kg ha^{-1}). Xie et al. [94] found that applying organic fertilizer after 21 days of composting increased yield by 15.1% (2687 kg ha^{-1}) compared with the control (2334 kg ha^{-1}). Pereira et al. [95] demonstrated a modest yield increase of 1,5% (3135 kg ha^{-1}) with the application of Stimulate® (a biostimulant based on 0.009% kinetin + 0.005% auxin + 0.005% gibberellic acid) compared to the control (3089 kg ha^{-1}).

Leite et al. [47] tested the inoculation of *Bradyrhizobium japonicum* with *Bacillus* spp. and arbuscular mycorrhizal fungi (AMF) through seed treatment under typical Latossol Vermelho soil. *B. japonicum* + AMF produced a yield of 4906 kg ha^{-1}, representing a 10.2% improvement (454 kg ha^{-1}) over the control (4452 kg ha^{-1}). In contrast, *B. japonicum* co-inoculated with *Bacillus* spp. yielded 4425 kg ha^{-1}, a slight decline of 27 kg ha^{-1} (−0.6%) relative to the control. These findings underscore the sensitivity of microbial interactions to strain compatibility and environmental conditions, highlighting the need to evaluate co-inoculant performance across diverse genetic backgrounds to determine whether synergistic effects are universal or genotype-specific.

Mishra et al. [96] reported that bioagents like Pseudomonas and *Trichoderma viride* improved soybean yield from 1373 to 1439 kg ha^{-1}, reflecting a 10.3–16.0% increase over the control (1245 kg ha^{-1}). The improved yields were attributed to the ability of these microbes to enhance nutrient availability and uptake essential for growth and seed development. Kristek et al. [97] reported that soil application of the microbiological preparation of Em-Aktiv, containing nitrogen-fixing *Bradyrhizobium* and *Azotobacter* ssp., as well as *Pseudomonas fluorescens* and *Bacillus* spp., increased yield to 392 kg ha^{-1} (11.6%) compared with 3378 kg ha^{-1} in the control. Similarly, Mondani et al. [98] found that under water deficit, foliar application of *Bacillus licheniformis* and *Bacillus subtilis* improved yield by 15.0% (2745 kg ha^{-1}) and 13.1% (2699 kg ha^{-1}), respectively, over the control (2386 kg ha^{-1}). These effects were likely due to enhanced nutrient use efficiency and stress mitigation under drought.

Collectively, these studies highlight that co-inoculation approaches can deliver synergistic benefits, with yield gains reaching up to 99.6%, particularly with *Bradyrhizobium japonicum* + *Azospirillum brasilense*. These improvements are driven by complementary functions such as nitrogen fixation, hormone stimulation, and nutrient solubilization. However, in Latossol Vermelho soils, microbial incompatibility may reduce inoculant efficacy, possibly due to competition for root exudates, underscoring the importance of compatibility and environmental conditions.

Fungal inoculants and non-rhizobial PGPR also exhibit strong yield-enhancing potential. Cely et al. [99] reported a yield increase of 39.7% (2984 kg ha^{-1}) using AMF (Rizo Plus® Rhizobacter) compared with the control (1508 kg ha^{-1}). Araújo et al. [38] similarly found that seed inoculation with Trichoderma asperellum increased the yield by 10.0% (4448 kg ha^{-1} vs. 4044 kg ha^{-1}). These enhancements are likely due to *Trichoderma* spp. stimulating root growth, nutrient uptake, and overall plant vigor [100]. Gonçalves et al. [101] evaluated foliar application of *Trichoderma viride* at different growth stages of

soybean and reported maximum seed yields of 5330.8 kg ha^{-1} at the vegetative stage and 5224 kg ha^{-1} at the early flowering stage, representing yield increases of 7.4% and 5.2%, respectively, whereas a slight decline (−0.2%) occurred when applied at the productive stage, compared with 4966 kg ha^{-1} in the control. This suggests that late-stage foliar treatments may disrupt hormonal balance or interfere with assimilate allocation.

Zilles et al. [102] reported that an *Endophytus* bacterial endophyte applied at a rate of 200 was most effective, boosting yield by 9.4% (3474 kg ha^{-1}), outperforming a fungal inoculant (ICB Nutrisolo Trichoderma) and the control (3175 kg ha^{-1}). Cruz et al. [103] observed a 5% yield increase (4552 kg ha^{-1}) with application of *Serratia marcescens* (BRM32114) (control yield 4335 kg ha^{-1}), while Lv et al. [104] found that seed inoculation with *Bacillus velezensis* (30 kg ha^{-1}) improved yields by 9.7% in sandy loam soils (2178 kg ha^{-1} control).

Overall, these studies indicate that AMF-, Trichoderma-, and Bacillus-based PGPR improve soybean yields by 5–40%, depending on species and application method. However, their effects are largely linked to enhanced root growth, improved phosphorus uptake, auxin production, and increased tolerance to drought through antioxidant and osmoprotectant pathways. Application timing is critical, as late foliar treatments may reduce yield.

Across microbial biostimulant categories, yield improvements ranged from 1% to nearly 100%, with the highest and most consistent gains observed under seed inoculation with *Bradyrhizobium*-based composite inoculants. Rhizobia reliably enhanced yield via biological nitrogen fixation, while co-inoculation expanded benefits through complementary mechanisms such as hormone stimulation and nutrient solubilization. Fungal inoculants and Bacillus-based PGPR improved yield by promoting root architecture, phosphorus uptake, and stress resilience. However, some co-inoculations (e.g., *Bradyrhizobium japonicum* + *Bacillus*) and poorly timed foliar applications (particularly, late application) reduced yield, emphasizing the need for precise inoculant matching and optimized application strategies.

A major research gap identified in this review is the limited systematic comparison of microbial biostimulants across diverse soybean genotypes. Future research must prioritize genotype–biostimulant interactions to determine whether the observed benefits are broad-spectrum or genotype-specific, critical knowledge for developing targeted and reliable microbial inoculation strategies. Overall, microbial biostimulants represent a promising tool for enhancing soybean productivity, but their success depends heavily on microbial compatibility, dosage, timing, and environmental conditions.

3.5. Interaction Effects of Non-Microbial and Microbial Biostimulants with Other Agro-Inputs on Soybean Yield

Intensive crop production and the imbalanced use of chemical fertilizers have led to soils deficient in essential nutrients and depleted in organic matter [105]. To address these challenges, integrated nutrient management strategies incorporating biostimulants, such as humic acids, fulvic acids, seaweed extracts, and biofertilizers, including *Azospirillum*, *Azotobacter*, *Bradyrhizobium*, and *Pseudomonas*, together with organic manure or mineral fertilizers, have been proposed to improve soil properties and enhance vegetative growth and productivity. Evidence consistently demonstrates that the combined use of biostimulants and other agro-inputs positively influences soybean yield through improved soil properties and enhanced nutrient uptake (Table S4).

Studies combining humic acid with microbial inoculants and macro- or micronutrients have reported significant yield gains. For instance, Miraezami et al. [58] demonstrated that humic acids combined with *Rhizobium* and *Azospirillum*, supplemented with micronutrients (Co, Mo, B), produced the highest yield. A maximum yield of 3288 kg ha^{-1} was recorded under humic acid + *Rhizobium* + *Azospirillum* + Co + Mo + B treatment, compared with 1288·kg ha^{-1} in the control—a 155.3% increase. Other treatment combinations (humic acids + *Rhizobium* + Co + Mo + B at 3125 kg ha^{-1} and humic acids + *Rhizobium* + Co + Mo,

2967 kg ha^{-1}) also improved yields by 142.6% and 130.4%, respectively. These findings highlight the synergistic benefits of combining microbial inoculants with micronutrients, particularly in enhancing nutrient bioavailability and reproductive development.

Similarly, Latifinia and Eisvand [106] explored the soybean responses to micro- and macronutrient deficiency with or without humic acid. Humic acid + nitrogen (N) + phosphorus (P) + iron (Fe) + molybdenum (Mo) increased yield by 90.3% (1772 kg ha^{-1}), while other treatments combinations such as humic acid + N + P + Fe, humic acid + N + Fe + Mo, humic acid + N + P + Mo, and humic acid + P + Fe + Mo also produced yields of 1706, 1679, 1619, and 1465 kg ha^{-1}, representing improvements of 83.2%, 80.3%, 73.9%, and 57.4%, respectively, compared with the control (931 kg ha^{-1}). These studies underscore the importance of integrated nutrient management in optimizing crop productivity.

Other combinations involving arbuscular mycorrhizal fungi (AMF), Rhizobium, seaweed extracts, and fertilizers have also shown positive yield effects. Cely et al. [99] evaluated *Rhizophagus clarus* inoculation and its effectiveness on growth, nutrient uptake, and yield under field conditions compared with conventional chemical fertilizer. The combination of AMF + 65 kg KCl + 200 kg ha^{-1} NPK (0:20:20) produced 3286 kg ha^{-1}, a 117.8% increase over the control (1508 kg ha^{-1}). Even with half the NPK dose, yield increased by 38.9% (2095 kg ha^{-1}), suggesting that AMF can enhance nutrient absorption efficiency and potentially reduce fertilizer requirements.

Similarly, Avornyo et al. [84] reported that TSP fertilizer combined with Rhizobium inoculation produced the maximum yield of 3666 kg ha^{-1} compared with 1772 kg ha^{-1} in the control—a 106.8% improvement. In medium loam soil, Ramazanova et al. [107] found that mineral phosphorus combined with geoumat products yielded 4130 kg ha^{-1}, a 34.5% increase over the control (3070 kg ha^{-1}). De Ávila et al. [108] showed that monoammonium phosphate (MAP) supplemented with humic acids (HA) and micronutrients produced 3448 kg ha^{-1}, a 6.4% improvement over the control (3239 kg ha^{-1}). These results emphasize the importance of pairing phosphorus fertilizers with nitrogen-fixing microbes to maximize nodulation and seed yield.

Khan et al. [32] reported that the combined application of seaweed extract, humic acids, and NPK fertilizer (300 kg ha^{-1}) increased soybean productivity by over 70%, highlighting the potential for seaweed-based inputs to complement humic substances and fertilizers in improving nutrient uptake and plant metabolism. Similarly, Hatipoğlu and Haliloğlu [80] found that combining high nitrogen application rates with *Bradyrhizobium japonicum* significantly enhanced productivity, with 280 kg ha^{-1} N yielding 3934 kg ha^{-1}—a 51.2% increase over the control (2598 kg ha^{-1}). Shome et al. [36] reported a remarkable 143.0% yield increase (2051 kg ha^{-1}) with a combined application of 50% nitrogen fertilizer + *R. japonicum* and 75% phosphorus + *P. striata*, compared with the control (844 kg ha^{-1}). Tandon and Dubey [109] also found that combining half the recommended NPK fertilizer with Biozyme Crop plus (*Ascophyllum nodosum*) biostimulant increased yield by 29.2% (3277 kg ha^{-1}) over the control (2536 kg ha^{-1}).

Seaweed extracts can also provide additive benefits when combined with other compounds. Kocira et al. [110] showed that formulations combining seaweed extracts with amino acids improved yields by more than 22.0%. Travençoli Rossetim et al. [82] demonstrated potential microbial incompatibility in dystrohumic cambisol soil. The most effective treatment—*Bradyrhizobium* + *Trichoderma harzianum* Sumbi-T5—yielded 4310 kg ha^{-1}, a 9.9% increase over the control (3920 kg ha^{-1}). This combination outperformed more complex consortia. Notably, combinations involving *Bradyrhizobium* + *Bacillus subtillis* or *Bradyrhizobium* + *Azospirillum brasilense* resulted in yield losses of 2.7% to 29.0%, indicating negative microbial interactions. However, Cruz et al. [103] observed a 5.5% increase

(4574 kg ha^{-1}) over the control (4335 kg ha^{-1}) through co-inoculation with strains BRM 32111 and BRM 32114.

Collectively, these studies demonstrate that interaction effects among microbial and non-microbial biostimulants with mineral fertilizers consistently enhance soybean yields. Yield improvement ranged from 22.0% to 155.3% (humic acid + *Rhizobium* + *Azospirillum* + micronutrients). These gains may be attributed to improved nodulation efficiency, biological nitrogen fixation, enhanced root architecture, and the stimulation of enzymatic and hormonal activities. Repke et al. [111] showed that combined micronutrients and biostimulants increased productivity by 22.0% through improved photosynthetic efficiency, stomatal regulation, and stress tolerance. Sheteiwy et al. [112] demonstrated that biofertilizers enhanced assimilate translocation to reproductive tissues, improving seed nutritional composition.

Despite these positive outcomes, variability across soil types, climates, and management conditions highlights the need for site-specific optimization. In particular, soil properties such as texture, pH, organic matter, and native microbial communities can strongly influence the efficacy of biostimulants, especially microbial inoculants. However, detailed soil characterization was inconsistently reported across studies, limiting systematic evaluation of soil-specific responses. A major unexplored source of variability is the differential response of soybean genotypes to these complex combinations. Future research should investigate dose–response relationships, application timing, genotype-specific reactions, and soil-context effects to refine integrated nutrient management strategies. Ultimately, biostimulant–fertilizer combinations hold strong promise for sustainable intensification of soybean production by reducing reliance on synthetic fertilizers while enhancing resilience and yield stability.

3.6. Effect of Non-Microbial and Microbial Biostimulants on Soybean Seed Quality

The results presented in Table S5 illustrate that both microbial and non-microbial biostimulants enhance soybean seed protein and oil content. These improvements are generally attributed to increased nutrient uptake, hormonal regulation, and improved carbon-nitrogen partitioning toward seed reserve formation.

Miraezami et al. [58] reported that foliar application of humic acid increased protein content to 34.98% and oil content to 13.81%, compared with 34.55% and 12.56%, respectively, in the control. Similarly, Latifinia and Eisvand [106] found that humic acid foliar treatment increased protein content to 29.76% and oil content of 12.86%, relative to 28.68% and 12.40% in the control. Overall, humic acid improved soybean seed protein content by 0.43–1.08% and oil content by 0.46–1.25%. These modest increases are associated with enhanced photosynthesis and improved micronutrient uptake, which stimulate enzymes involved in protein and lipid biosynthesis [113,114].

Kristek et al. [97] revealed that *Bacillus subtilis* and *Bacillus licheniformis* increased seed protein content to 30.70% and 30.60% and oil content to 20.70% and 20.40%, respectively, compared with 27.70% (protein) and 18.80% (oil) in the control. This corresponds to protein increases of 3.00% and 2.90% and oil increases of 1.90% and 1.60%. Co-inoculation with *Bradyrhizobium* and *Azospirillum brasilense* increased protein content to 35% compared with 33.10% in the control [115]. Likewise, Procházka et al. [116] found that a complex treatment applied to a loam arenosol cambisol improved protein (33.43%) and oil (19.09%) over the control protein (33.34% and 18.74%).

Miraezami et al. [58] also evaluated seed inoculation with Rhizobium and its combination with *Azospirillum*, reporting protein and oil contents of 35.68% and 15.86% under the combined treatment, and 34.89% protein and 13.86% oil under Rhizobium alone, compared with 31.41% protein and 12.56% oil in the control. These results indicate improvements of 4.27% in protein and 3.3% in oil under the combined inoculation, and 3.48% in protein

and 1.3% in oil under Rhizobium alone. This supports the synergistic effect likely driven by the combined action of biological nitrogen fixation by Rhizobium and phytohormone production by *Azospirillum*, which together enhance nutrient assimilation and stimulate carbon partitioning toward seed reserve formation. These findings further reinforce the hypothesis that co-inoculation with beneficial microbes can induce synergistic biochemical and physiological responses, resulting in improved seed quality [117,118].

Many studies confirm the efficacy of foliar application. A single spray of Atonik increased protein content by 3.45% [119], while the Terra Sorb Complex resulted in a 3.2% increase [33]. Szparaga et al. [120] similarly reported that Levisticum officinale extract applied at 300 mL L^{-1} produced a modest protein increase of 1.38% (36.7%) compared with the control (35.34%). In another study, Kocira et al. [121] found that a single application of a biostimulant containing *Ascophyllum nodosum* and free amino acids (1.00%) enhanced protein content by 1.2% (37.8%) relative to the control (36.6%).

Application of Em-Aktiv—a biostimulant blend containing *Bradyrhizobium*, Azotobacter, *Pseudomonas fluorescens*, and Bacillus—further supported the role of microbial agents. Kristek et al. [97] reported that soil application of 30 L ha^{-1} Em-Aktiv resulted in 38.2% protein and 22.53% oil content of soybean seed. A combined treatment (30 L ha^{-1} soil application + two foliar sprays at 2 × 6 L ha^{-1}) produced 36.82% protein and 22.37% oil, compared with 37.5% protein and 21.97% oil in the control. These findings indicate a 0.7% increase in protein and 0.56% increase in oil under soil application alone. Beneficial microorganisms such as *Bacillus subtilis*, *Bacillus licheniformis*, and *Bradyrhizobium* likely enhance soybean seed quality by promoting nutrient assimilation and metabolic activity, although the magnitude of improvement varies with application method. Notably, combining soil and foliar treatments slightly reduced protein content by 0.68%, while maintaining oil gains (+0.40%), suggesting possible antagonistic interactions, suboptimal timing or reduced microbial viability.

Hashem et al. [122] attributed the benefits of *Bacillus subtilis* to nitrogen fixation, extracellular enzyme production, and reduction in anti-nutritional factors (e.g., trypsin inhibitors), thereby increasing crude and soluble proteins. Travençoli Rossetim et al. [82] found that a combined inoculation of *Bradyrhizobium*, *Bacillus subtilis*, and *Trichoderma harzaianum* Sumbi-T5 in a dystrohumic Cambisol soil yielded the highest protein content (42.50%), representing a 57.40% increase over the control (27.00%). However, several microbial combinations substantially reduced oil content (by 15–34.1%), indicating potential microbial incompatibility.

Further improvements were observed under integrated nutrient–biostimulant strategies. Khan et al. [32] evaluated humic acid (9.6 kg ha^{-1}), seaweed extract (24 kg ha^{-1}), and NPK (350 kg ha^{-1}), finding that the full combination produced a maximum protein content of 40.75% compared with 33.44% in the control—an improvement of 7.31%. The combination of seaweed extract + NPK yielded an oil content of 20.84% relative to 15.35% in the control, a 5.49% increase. Miraezami et al. [58] also reported protein values ranging from 30.85 to 37.15% and oil content from 16.18 to 18.47% under treatments with humic acid + *Rhizobium* + *Azospirillum* + Co + Mo + B, compared with 34.98% protein and 12.56% oil in the control. Similarly, Latifinia and Eisvand [106] recorded protein contents of 29.61–30.85% and oil content of 13.02–15.19% under humic acid + N + P + Fe + Mo, compared with 28.68% and 12.40% in the control. Hatipoglu and Haliloglu [80] further showed that high nitrogen application (280 kg ha^{-1}) combined with *Bradyrhizobium japonicum* maximized protein content (40.10%), but reduced oil content by up to 8.47%, reflecting a metabolic shift toward protein synthesis.

Overall, both microbial and non-microbial biostimulants increased soybean seed protein and oil content, with improvements ranging from modest (e.g., 0.43% protein; 0.46% oil with

humic acid foliar spray) to substantial (7.31% protein; 5.49% oil under humic acid + seaweed extract + NPK). Microbial inoculants—particularly *Rhizobium* co-inoculated with *Azospirillum*, and blended products such as Em-Aktiv—enhanced seed quality through mechanisms including nitrogen fixation, hormone modulation, and stress alleviation. Nonetheless, variable responses (e.g., reduced protein under combined Em-Aktiv soil + foliar application) underscore the importance of inoculant compatibility, application method, and timing.

Future research should prioritize optimizing co-application strategies—such as humic acid + *Rhizobium* + *Azospirillum* + NPK or seaweed extract + *Azospirillum* + micronutrients—to maximize synergistic effects on soybean nutritional quality across diverse environments.

3.7. Practical Considerations, Environment, Cost-Effectiveness, and Scalability

Despite the reported agronomic benefits of biostimulants, the studies included in this review rarely reported data on their cost-effectiveness or scalability under commercial farming conditions. For instance, information on product costs, application expenses, cost–benefit ratios, and farm-scale performance was largely absent, limiting quantitative economic assessments. Consequently, this data gap highlights the critical research need for future studies that integrate yield and quality responses with economic evaluations and on-farm validation to promote informed adoption of biostimulants in soybean production.

Furthermore, the mechanistic basis of synergistic effects with fertilizers involves enhanced nutrient uptake, root growth, hormone signaling, antioxidant activity, and metabolic pathways, but the precise molecular mechanisms in soybean remain incompletely understood. In addition, biostimulant efficacy may vary between organic and conventional farming systems due to differences in nutrient availability, soil microbiomes, and management practices, though comparative studies are limited.

From a practical standpoint, the standardization of formulations and application protocols is essential to achieve reproducible outcomes. This includes clear product characterization, harmonized dosing and timing guidelines for major agroecological zones, and transparent reporting of soil, environmental, and crop genotype information.

Moreover, sustainability and environmental impacts also warrant consideration. For example, large-scale production of seaweed extracts and humic acids may have ecological footprints, such as coastal ecosystem disturbance, energy use, or land impacts. Similarly, microbial biostimulants can persist in soil, and although most strains are target-specific, their effects on non-target crops, native microbial communities, and ecosystems are not fully understood.

4. Conclusions

This systematic review synthesized current evidence on the role of biostimulants in sustainable soybean production, with a specific focus on yield performance, seed quality, and strategic application approaches. In line with the first objective, the reviewed studies consistently demonstrate that both non-microbial (humic substances, amino acids, seaweed extracts) and microbial biostimulants (e.g., *Bradyrhizobium japonicum*, PGPR, AMF, *Trichoderma* spp.) improved seed yield and quality traits. Yield responses ranged widely (100–5522 kg ha^{-1}), reflecting improvements in nutrient use efficiency, root development, stress resilience, and key physiological processes. Interactive effects were also evident, indicating that the synergistic application of biostimulants with mineral fertilizers can further enhance productivity and support integrated crop management approaches. In parallel, biostimulant application enhanced seed quality, increasing protein content by 0.46–7.31% and oil content by 0.43–5.49%, while some combined treatments improved quality components by more than 45%, confirming their dual potential to increase both productivity and quality.

Addressing the second objective, this review highlights substantial variability in biostimulant efficacy, identifying several critical knowledge gaps. Treatment performance was strongly influenced by application method, environmental conditions, soil properties, and microbial compatibility, while synergistic effects with mineral fertilizers further complicated response patterns. Although the mechanisms underlying these interactions are often attributed to enhanced nutrient uptake, hormone signaling, antioxidant activity, and metabolic regulation, the precise molecular and physiological pathways in soybean remain insufficiently resolved. Moreover, comparative evidence across organic and conventional farming systems is limited, and the persistence of microbial biostimulants in soil raises unanswered questions regarding their long-term effects on native microbial communities and agroecosystem functioning.

In relation to the third objective, the findings indicate that optimized biostimulant strategies—whether applied alone or integrated with mineral fertilizers—offer substantial potential to support sustainable soybean production. However, achieving reliable and reproducible outcomes requires greater standardization of product formulations, clearer guidelines for application timing and dosage, and transparent reporting of environmental, soil, and genotype-specific factors. When appropriately implemented, biostimulants can contribute to reduced dependency on synthetic inputs, improved resource-use efficiency, and enhanced resilience of soybean cropping systems.

Future research should prioritize integrating agronomic performance with economic assessments and on-farm validation to better quantify the cost–benefit ratio of biostimulant use under real production conditions. Greater emphasis is also needed on unraveling the mechanistic basis of synergistic effects between biostimulants and fertilizers, particularly at the molecular and metabolic levels in soybean, while expanding comparative studies across farming systems will be essential to clarify context-dependent responses and improve the transferability of results. From a sustainability perspective, the environmental footprint of biostimulant production and use warrants closer scrutiny. The large-scale extraction of seaweed or humic substances may carry ecological risks, while the long-term ecological impacts of persistent microbial inoculants on non-target organisms and soil biodiversity remain poorly understood. Addressing these challenges through interdisciplinary research, harmonized protocols, and system-level assessments will be critical to fully exploit the potential of biostimulants as a cornerstone of sustainable soybean production.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su18020636/s1: Table S1: Influence of humic acid and amino acids on soybean seed yield; Table S2: Influence of seaweed extracts on soybean seed yield; Table S3: Influence of beneficial bacteria and fungi on soybean seed yield; Table S4: Interactive effect of biostimulants and other fertilizer types or agro-inputs on soybean yield; Table S5: Effect of biostimulants on soybean quality traits; PRISMA 2020 checklist.

Author Contributions: Conceptualization, E.A.A., M.S.N., A.O., E.J.D. and E.T.K.; writing—original draft preparation, E.A.A., M.S.N., A.O., E.J.D. and E.T.K.; writing, review and editing, E.A.A. and E.T.K.; visualization, E.A.A.; supervision, E.T.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: Supported by the University of Debrecen Program for Scientific Publication.

Conflicts of Interest: The authors declare no conflicts of interest.

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