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REVIEW

Maize Grain Yield and Quality Improvement Through Biostimulant Application: a Systematic Review

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Abstract

Increasing the productivity of cereals such as maize while protecting the environment remains a fundamental impetus of healthy food production systems. The use of biostimulants is one of the sustainable strategies to achieve this balance, although the ability of biostimulants to enhance maize productivity varies. Moreover, research on the efficacy of biostimulants is ubiquitous with limited comprehensive global analysis. In this context, this systematic review evaluated the sole and interactive effects of biostimulants on the yield and quality of maize grain from a global perspective. Changes in yield (t ha^{-1}), protein content (%), starch content (%) and oil content (%) of maize grain were assessed. Results revealed that sole and combined application of biostimulants significantly improved grain yield. Irrespective of the region, the highest and the lowest grain yields ranged between 16-20 t ha^{-1} and 1-5 t ha^{-1}, respectively. In sole application, the promising biostimulants were chicken feather (16.5 t ha^{-1}), and endophyte *Colletotrichum tofieldiae* (14.5 t ha^{-1}). Sewage sludge × NPK (15.4 t ha^{-1}), humic acid × control release urea (12.4 t ha^{-1}), *Azospirillum brasilense* or *Bradyrhizobium japonicum* × maize hybrids (11.6 t ha^{-1}), and *Rhizophagus intraradices* × earthworms (10.0 t ha^{-1}) had higher yield for the interactive effects. The effects of biostimulants on grain quality were minimal, and all attributes improved in the range from 0.1 to 3.7%. Overall, biostimulants had a distinct improvement effect on yield, rather than on the quality of grain. As one way of maximising maize productivity, soil health, and the overall functioning of crop agroecosystems, the integrated application of synergistic microbial and non-microbial biostimulants could provide a viable option. However, the ability to produce consistent yield and quality of grain improvement remains a major concern.

Keywords Biostimulants · Grain · Maize · Oil content · Protein content · Starch content · Yield

1 Introduction

Maize (*Zea mays* L.) is the second most important widely cultivated crop after wheat with a global production estimated at 1137 million tons (Erenstein et al. 2022) and significantly contributes to global food security (Díaz-González et al. 2020; Efthimiadou et al. 2020; Erenstein et al. 2022). However, its productivity is constrained by abiotic stresses such as climate change (Jiménez-Arias et al. 2022; Mohammed et al. 2022; Széles et al. 2023) and soil degradation especially deteriorating soil fertility (Gomiero, 2016) among other factors. Abiotic stresses account for 50% of yield losses in crop production (Nassar et al. 2023), with nutrient stress or unbalanced nutrient supply being one of the fundamental factors (Javeed et al. 2019; Rácz et al. 2021). Climate change alters optimum soil fertility attributes such as appropriate nutrient level, moisture content, temperature, organic matter and microbiota. Addressing this challenge requires sustainable agrotechnologies that improve soil productivity while maintaining environmental and human health (Nakayan et al. 2013; Megali et al. 2015; Długosz et al. 2020; Ocwa et al. 2023). Conventionally, the use of chemical fertilisers raises concerns related to soil

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and water pollution (Bhattacharjee et al. 2008; Adesemoye and Kloepper 2009; Canellas et al. 2013; Alori et al. 2017; Chen et al. 2020). Yet, environmental protection is one of the key objectives of healthy food production systems (Popescu 2019). Some ecological strategies include increasing nutrient uptake through biostimulant application (Yakhin et al. 2017; Abbott et al. 2018; Jiménez-Arias et al. 2022) without additional nutrient input (Ördög et al. 2021). Plant biostimulants are designated as metabolic enhancers, plant strengtheners, biofertilisers, plant probiotics and biostimulators (Sible et al. 2021). These products are materials or substances such as seaweed extracts, humic substances, amino acids, and plant-growth-promoting bacteria that can modify plant physiological processes in a way that provides benefits for growth or development, or stress response upon their application (Halpern et al.2015). Globally, the biostimulant market is predicted to reach USD 5.1 billion by 2027, compared to USD 3 billion in 2021 (Market research 2021; Corsi et al. 2022). This production and marketing trend indicates increased application of biostimulants in crop production (Craigie 2011; Nkebiwe et al. 2016). Biostimulants improve soil health through bioremediation of soil contaminated by pesticides (Tejada et al. 2018), while enhancing soil fertility (Chandanie et al. 2005; Aquino 2019) and crop production.

In terms of non-microbial biostimulants; humic acids improve soil nutrient availability and the abiotic stress response of crops (Osman and Rady 2012; Popescu, 2019; Chen et al. 2022; Guo et al. 2022). At the same time, the degree of crop response depends on soil conditions (Szczepanek and Wilczewski 2016) and biostimulant formulation (Ortega and Fernandez 2007; Verlinden et al. 2009). On the same note, seaweed extracts improve maize productivity by ameliorating water stress (Trivedi et al. 2018a) through increased activity and concentration of non-enzymatic and enzymatic antioxidants (Trivedi et al. 2018b). In addition, Kumar et al. (2020) explained that *Kappaphycus* seaweed extract application causes beneficial changes in expression pattern of several genes, modulation of biological processes and plant productivity under soil moisture stress. Quantitatively, Trivedi et al. (2018a) reported that *Kappaphycus* seaweed extract improved yield by 13.5%, 21.7%, and 36.4% under well-irrigated, moderately irrigated, and severe water conditions, respectively. Similarly, the highest yield increment of 32% was recorded when *Kappaphycus* seaweed extract was applied at V5 + V10 + V15 stages under drought (Trivedi et al. 2022). Relatedly, glycine betaine biostimulant under field conditions increased maize grain yield while the protein and carbohydrate content were the same as the control (Jiménez-Arias et al. 2022).

Microbial biostimulant formulations from plant growth promoting bacteria (PGPB), arbuscular mycorrhiza fungi (AMF), and phosphorus solubilising microorganisms (PSM) enhance maize production by fixing nitrogen (Ahmadi-Rad et al. 2016; Romero-Perdomo et al. 2017), solubilising mineral phosphates (Mpanga et al. 2019), generating phytopathogen antagonistic environment (Bahadur et al. 2007) and producing plant growth hormones (Ahmad et al. 2008; Zainab et al. 2021). The ability of PGPB to produce desired effects depends on the level of Indole Acetic Acid (IAA) production, generation of smelling salts (ammonia), siderophore activity and rhizosphere conditions (Romero-Perdomo et al. 2017) and the severity of the biotic and abiotic stresses. For example, Nkebiwe et al. (2016) reported no significant grain yield increment by *Pseudomonas* bacterial inoculation due to low severity of environmental stress factors. In terms of grain quality, Berta et al. (2014) revealed that *Pseudomonas fluorescens* Pf4 mainly increased starch and reduced protein content of the maize grain while AMF increased protein and reduced starch content of maize grain. According to Smith and Smith (2011), AMF improves protein content by ameliorating phosphorous deficiency and improving nitrogen use efficiency. In addition, the efficiency of availability and utilisation of phosphorus depends on the solubility of the phosphorus sources (Ghorchiani et al. 2018).

The mechanism of productivity enhancement by biostimulants is not evidently defined (Efthimiadou et al. 2020). Therefore, optimising biostimulant use necessitates quantifying potential isolated and combined effects. In addition, positive impact of biostimulants under laboratory conditions may become suboptimal under field conditions (Naveed et al. 2014; Mpanga et al. 2019). Variation in field efficacy is caused by interaction between biostimulants and soil properties (Rojas-Tapias et al. 2012; Tripaldi et al. 2017), host plant factors, soil microflora (Berta et al. 2014) and climatic conditions. Additionally, the inherent biostimulant factors, sole or combined use (Gümüs and Seker 2015; Długosz et al. 2020) and concentration (Szczepanek and Wilczewski 2016) may elicit different crop responses. Canellas (2013) reported that combined application of humic substances and endophytic diazotrophic bacteria improved maize grain yield by 65%, compared to 20% by sole bacteria. Contrasting to this finding, Abbasi et al. (2015) revealed that sole and combined application of phosphate-solubilising bacteria and diammonium phosphate did not significantly affect yield. Accordingly, Lino et al. (2019) reported that interaction between cattle manure fertilisation × mycorrhizal inoculation significantly increased yield only in the second year of the experiment. Dineshkumar et al. (2019) noted that biostimulant interactive effects improved yield and reduced the protein and carbohydrate content of maize grain. Generally, the inconsistencies on the effects of biostimulants under different experimental sites, seasons and/or years necessitate proper evaluation (Baloyi et al. 2023). This makes understanding application of biostimulants on plant production to remain elusive (Torun and Toprak 2020; Liu et al. 2022).

Numerous reviews have focused on identifying the main types of biostimulants and modes of action (Sible et al. 2021;

Abir et al. 2022; Bhupenchandra et al. 2022). A review by Yuniati et al. (2022) recommended soil or seed treatment testing of biostimulants that have positive impact by foliar application. According to Castiglione et al. (2021), the success of using microbial biostimulants requires correct selection of beneficial microorganism's consortia. In addition, limited literature has explored combined application of PGPB and humic substances (Olivares et al. 2017). From these reviews, it is evident that aggregation of results of published literature is necessary to highlight the consensus in positive results. This will allow replicability of positive impacts on certain plant species (Montoneri et al. 2022), or provide direction for future investigations. None of these reviews explicitly investigated the response of yield and quality of maize grain to biostimulants. Yet, most biostimulant products are uncharacterised with limited robust independent validation (Yakhin et al. 2017). Together with the unpredictability in replicating the positive effects of biostimulants under laboratory conditions in the field, there is uncertainty on the direction of biostimulant utilisation to improve maize production. Therefore, this systematic review evaluated the sole and interactive effects of biostimulants on the yield and quality of maize grain from a global perspective.

2 Materials and Methods

2.1 Document Identification and Search Strategy

The comprehensive literature search was conducted in Scopus, as it is the most complete and extensively used database archiving millions of high-quality articles from reputable journals. The search string ((“biostimulant*” OR “phytostimulat*” OR “biofertiliser*” OR “microorganism*” OR “humic acid*” OR “fluvic acid” OR “seaweed extract*”) AND ((“maize” OR “*Zea mays*” OR “corn”)) AND (“yield” OR “productivity” OR “grain quality”)) was used for the period 2011-2023. We desisted from including disaggregated forms of microorganisms such as “fungi” and “bacteria” in the search because the pilot output brought thousands of articles, majorly on plant pathology, which were out of context for this study. The search strategy is summarised in Fig. 1.

2.2 Document Exclusion and Inclusion Criteria

Both the titles and abstracts were screened and where uncertain, the full text was screened. Articles that passed this step were fully reviewed. The inclusion criteria were that only original research articles that reported the effect of biostimulants on the yield and quality of maize grain under field conditions were considered. Details of the articles inclusion and exclusion criteria are summarised in Box 1.

Box 1 Title and abstract screening criteria (inclusion and exclusion)

No: Maize included in the study but no and/or unclear biostimulants information.

No: Biostimulants were included in the study but no quality of maize grain or yield information.

No: Both maize and biostimulants included in the study but no quantitative or unclear direction (qualitative evidence) of how the biostimulants affect yield and/or quality of maize grain.

No: Maize intercrop and biostimulants were included in the study. If the effect of biostimulant on sole maize and/or intercrop is not reported.

No: Biostimulant is combined with other fertilizers or agro-inputs but no effect of sole biostimulant and/or interactive effects on yield and/or quality of maize grain is reported.

Yes: Study is eligible for inclusion in full-text review if it passed the above criteria.

NB: Articles with quantitative data and qualitative evidence effect of biostimulants on yield and quality of maize grain were included in the study after full text article review.

2.3 Data Extraction and Analysis

Data such as yield (t ha^{-1}), protein, starch, and oil content of maize grain were extracted from Tables and Figures. Webplotdigitizer (version 4.6) was used to extract data presented in Figures (Rohatgi 2022). Data on the interactive effect of biostimulants with agronomic practices and/or inputs such as chemical fertilisers and irrigation (drought stress) on yield and quality of maize grain were also extracted. The other data extracted included: location of the study (country), details of biostimulants, maize varieties, soil type in the study sites, and method of biostimulants application. Where the parameters were presented in two or more different seasons, an average value was calculated (AlFaris et al. 2021), except where season or year was the principal factor tested with biostimulants. The grain yield and quality attributes change due to biostimulants effect and/or interaction between biostimulants and agronomic practices were calculated (Singhal et al. 2012; Gavilanes et al. 2020; Chen et al. 2021a). The sole and interactive effects of biostimulants versus control at continental level were analysed using the T test. Accordingly, detailed descriptive analysis and reflections were conducted to identify possible future research gaps. It is also worthwhile to note that for the attributes of the quality of maize grain reporting; only articles reported in percentage were used.

3 Results and Discussion

3.1 Categorisation of Included Literature

Resulting from article evaluation, 69 articles were included in this study, with continental distribution as Asia (46.4%), South America (23.2%), Europe (17.4%),

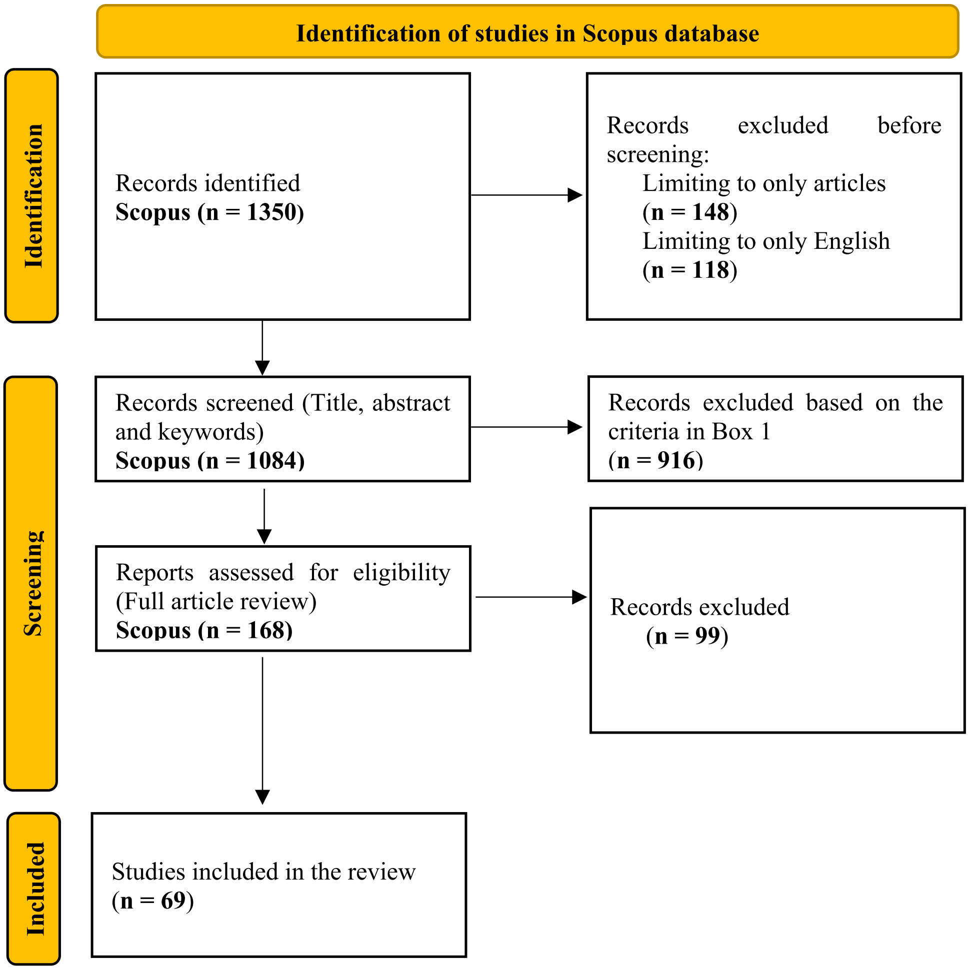


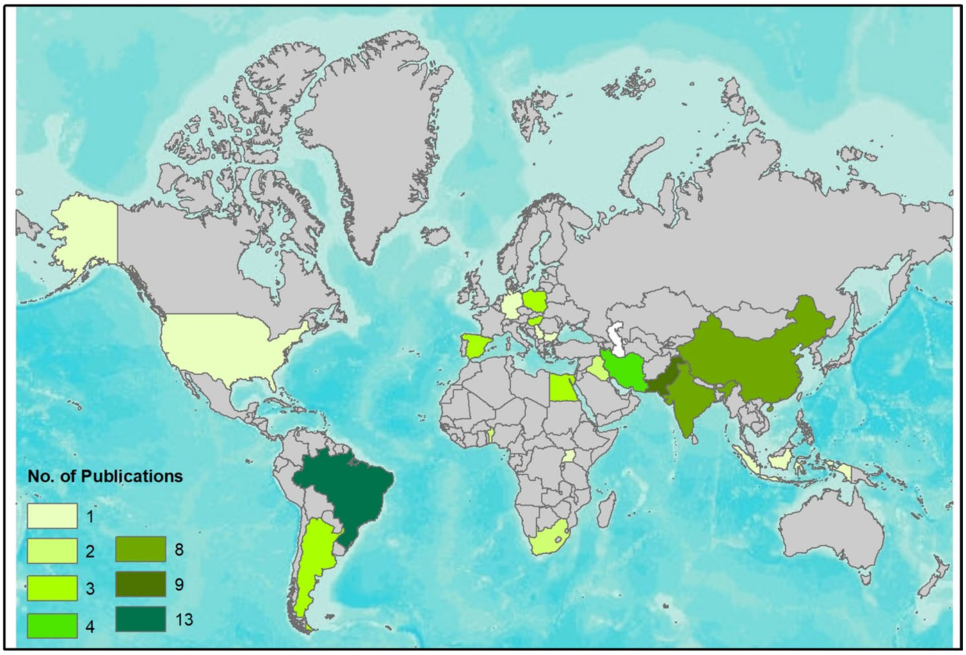
Fig. 1 Criteria applied during literature search

Africa (11.6%), and North America (1.4%). The country distribution of articles is presented in Fig. 2. Overall, global distribution of the articles depicts the increasing interest in utilising biostimulants to increase maize production. The nature and composition of biostimulants investigated varied from humic acids, PGPB, AMF, PSM, phytohormones, amino acids, seaweed extracts, sewage sludge, biochar biofertiliser, and chicken feather biostimulant. The biostimulants were utilised through sole application and/or in combination with other agro-inputs, such as other organic and chemical fertilisers, fungicides, irrigation, and maize genotypes.

3.2 Effect of Sole Biostimulants on Grain Yield of Maize

The effect of sole biostimulant application on grain yield at continental level was significant ($p<0.05$) only in Asia and South America (Fig. 3a). Critical analysis of all articles reviewed revealed that biostimulants increased maize grain yield, though a few decreased grain yield as compared to the control (Table 1). Yield improvements varied according to the nature of biostimulants, soil types and application methods. For example, a study by Anzuay et al. (2023) in Argentina revealed that *Enterobacter* sp. J49 recorded grain yield of 8.9 t ha^{-1} compared to the control (7.96 t ha^{-1}), representing 11.8% (0.94 t ha^{-1}) increment. Ördög et al. (2021) in Hungary reported that foliar application of Cyanobacteria (*Nostoc piscinale*) produced yield of 10.33 t ha^{-1} as compared to the control of 9.4 (t ha$^{-1)}$, revealing 9.8% (0.93 t ha^{-1}) increment. In Brazil Silva et al. (2022) reported that *Azospirillum brasilense* applied through seed inoculation produced grain yield of 5.6 t ha^{-1} as compared to 4.48 t ha^{-1} in the control, showing 25% (1.1 t ha^{-1}) improvement. Generally, seed inoculation promotes earlier establishment of maize as well as resistance to abiotic stress. Meanwhile, foliar application supplies nutrients to maize at critical stages, improving nutrient use efficiency and agronomic efficiency (Anzuay et al. 2023). Consequently, it is worthwhile to investigate the combined effect of seed inoculation with *Azospirillum brasilense* combined with foliar application of *Nostoc piscinale* or *Azospirillum brasilense* + *Enterobacter* sp. J49 on grain yield. This will reveal the possibility of existence of synergistic or antagonistic effects on yield.

Fig. 2 Distribution of the articles by country



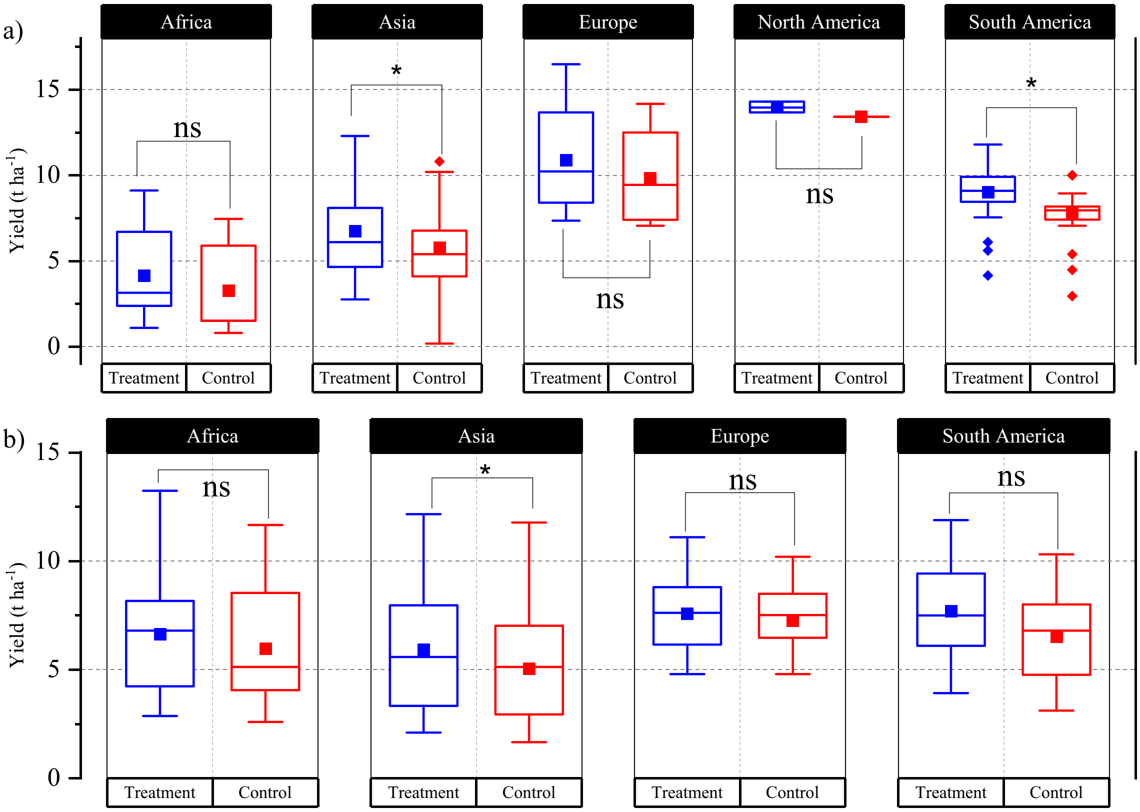


Fig. 3 Continental effect of biostimulants application on grain yield of maize: a) Sole application, b) integrated application.

Mutualistic association between most microorganisms is common. However, *Azospirillum brasilense* produces other molecules and siderophores that reduce fungal mycelial growth (Silva et al. 2022), hence a possibility of antagonistic effects. Meanwhile, Chen et al. (2021b) tested the effect of different bacterial species on a soil with low nitrogen and

Table 1 Effect of sole biostimulants application on grain yield of maize

Reference	Country	Soil type (experimental site)	Treatment	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Francis et al. (2016)	USA	Desha silt loam	Foliar blend levels 1.2 l ha^{-1} 2.3 l ha^{-1} 3.5 l ha^{-1} Control NB: Foliar Blend® composition - complex carbohydrates, plant nutrients and blend of enzymes, amino acids, and a host of nutritional supplements not supplied by ordinary N-P-K fertilizers	13.67 13.96 14.3 13.42	0.25 0.54 0.88	1.9 4.0 6.6	Foliar
Dai et al. (2023)	China	Sandy loam and clay (two sites)	*Lysobacter antibioticus* 13–6 + additives 2% tebuconazole + additives control	12.23 12.19 10.81	1.42 1.38	13.14 12.77	Soil
Anzuay et al. (2023)	Argentina	Typic Hapludoll	*Enterobacter* sp. J49 Control (without inoculation or fertilization)	8.9 7.96	0.94	11.8	-
Thomé et al. (2023)	Brazil	Oxisol	Phytohormones and nicotinamide Control	6.1 5.4	0.7	13.0	Foliar
Kalman et al. (2022)	Hungary	Classification unspecified (physco-chemical properties detailed)	PGPB *Rhodopseudomonas palustris* + *Lactobacillus plantarum* + *Lactobacillus casei* + *Saccharomyces cerevisiae* *Bacillus pumilus* + *Pseudomonas putida* *Bacillus megaterium* + *Pseudomonas fluorescens* Control	8.9 9.3 9.9 8.8	0.1 0.5 1.1	1.1 5.7 12.5	-
Kong et al. (2022)	China	Typic Hapludalf soil	Humic acid urea, 168 kg N hm^{-2} Humic acid urea, 168 kg N hm^{-2} Humic acid urea, 216 kg N hm^{-2} Humic acid urea, 240 kg N hm^{-2} Urea, 240 kg N ha^{-1} Control (no nitrogen)	7.4 7.8 8.5 8.1 7.5 5.4	2 2.4 3.1 2.7 2.1	37.0 44.4 57.4 50 38.9	Soil
Abdo et al. (2022)	Egypt	Alluvial clay	Humic acids (3 g L^{-1}) Amino acids (3 g L^{-1}) Humic acids (3 g L^{-1}) + Amino acids (3 g $^{-1}$) control	6.7 7.4 7.8 5.9	0.8 1.5 1.9	13.6 25.4 32.2	Foliar

Table 1 (continued)

Reference	Country	Soil type (experimental site)	Treatment	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Li et al. (2022)	China	Fluvo-aquic soil	Gamma-aminobutyric acid Humic acid(100 mg L^{-1}) Chitosan(100 mg L^{-1}) Trehalose(100 mg L^{-1}) control	5.84 5.97 5.99 6.4 6.2	- 0.36 - 0.23 - 0.21 0.2	-5.8 -3.7 -3.4 3.2	Foliar
Silva et al. (2022)	Brazil	Rhodic Haplustox (clayey Oxisol)	*Azospirillum brasilense* control	5.61 4.48	1.13	25.2	Soil (seed inoculation)
Agbodjato et al. (2022)	Benin	Ferruginous soil	Mycorrhizal fungi strains *Acaulosporaceae* *Glomeraceae* control	2.38 2.3 1.93	0.45 0.37	23.3 19.2	Soil (seed coating)
Kumar et al. (2022)	India	Clay loam	Polyfeed 1 % at 20 and 45 DAS DAP 2% at 20 and 45 DAS Humic acid 40 ppm at 20 and 45 DAS Seaweed 10 % at 20 and 45 DAS Panchagavya 3 % at 20 and 45 DAS Vermiwash 2 % at 20 and 45 DAS Control water spray DAS – Days after sowing	4.82 4.62 4.4 4.22 4.51 4.72 3.85	0.97 0.77 0.55 0.37 0.66 0.85	25.2 16.7 14.3 9.6 17.1 22.1	-
Ördög et al. (2021)	Hungary	Danubian Alluvial soil and leached chernozem soil	Cyanobacteria (*Nostoc piscinale)* Control	10.33 9.4	0.93	9.8	Foliar

Table 1 (continued)

Reference	Country	Soil type (experimental site)	Treatment	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Chen et al. (2021b)	China	Typical black soil (Udolls)	Low nitrogen *Sinorhizobium sp*. A15 (2.0 × 105 cells per seed) *Bacillus sp*. A28 (2.0 × 105 cells per seed) *Sphingomonas sp*. A55(2.0 × 105 cells per seed) *Enterobacter sp*. P24(2.0 × 105 cells per seed) Non-inoculated in low-N soil Low phosphorus *Sinorhizobium sp*. A15 (2.0 × 105 cells per seed) *Bacillus sp*. A28 (2.0 × 105 cells per seed) *Sphingomonas sp*. A55(2.0 × 105 cells per seed) *Enterobacter sp*. P24(2.0 × 105 cells per seed) Non-inoculated in conventionally fertilsed soil	11.5 11.3 12 11.2 10.2 11.9 12.1 12.1 12.3 10.2	1.3 1.1 1.8 1.0 1.7 1.9 1.9 2.1	12.7 10.7 17.6 9.8 16.6 18.6 18.6 21.56	Seed inoculation
Gerhards et al. (2021)	Benin	Ferruginous tropical loamy sand	Biostimulant ComCat® concentrations 200 gha^{-1} 100gha^{-1} 50gha^{-1} Control	1.2 1.1 1.2 0.8	0.4 0.3 0.4	50 37.5 50	Foliar
Mussarat et al. (2021)	Pakistan	Silt loam	Humic acid (5 kg HA ha^{-1}) Control	2.76 1.84	0.92	50	Soil
Nascimento et al. (2021)	Brazil	Ultisol	*Bacillus sp.* Control	4.15 2.95	1.2	40.7	Seed inoculation
de Sousa et al. (2021)	Brazil	Red Oxisol	*Bacillus* bacteria strains B2084 B119 B116 B70 Control (non-inoculated)	9.1 8.6 11 8.37 8.09	1.01 0.51 2.7 0.28	12.5 6.3 33.4 3.5	Seed coating

Table 1 (continued)

Reference	Country	Soil type (experimental site)	Treatment	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Azeem et al. (2021)	Pakistan	Silty-loam	Humic acid doses 1.5 kgha^{-1} 3kgha^{-1} 4.5 kgha^{-1} Control	3.3 3.64 3.78 2.76	0.54 0.88 1.02	19.6 31.8 37.0	Soil
da Cunha et al. (2021)	Brazil	Dystrophic Red Yellow Argisol	Diazotrophic bacteria *Azospirillum brasilense* *Bradyrhizobium japonicum* *Azospirillum brasilense* + *Bradyrhizobium japonicum* No inoculation (50% of the recommended N dose (40kgha^{-1})	9.28 9.78 8.75 7.06	2.22 2.72 1.69	31.3 38.5 27.8	Seed inoculation
Díaz-González et al. (2020)	Spain	-	Endophyte *Colletotrichum* Ct0861 doses CtST1-Zm (2×10^{7}) CtST2-Zm(2×10^{8}) CtST3-Zm (2×10^{9}) M-Zm (control)	14.4 14.1 15.2 12.5	1.9 1.6 2.7	15.2 12.8 21.6	Seed inoculation
Kapela et al. (2020)	Poland	Luvisols, sandy type	Different biostimulants Asahi SL® (0.60 dm^{3} ha^{-1}) Zeal® (2.00 dm^{3} ha^{-1}) Improver® (1.00 dm^{3} ha^{-1} and 0.60 dm^{3} ha^{-1}) Control	8.4 8.08 7.89 7.4	1 0.68 0.49	13.5 9.2 6.6	Foliar
Gavilanes et al.(2020)	Brazil	Eutrudox and Oxisols	*Anabaena cylindrical* + *Azospirillum brasilense* *Anabaena cylindrical* *Azospirillum brasilense* Control NB: Values from different sites averaged	9.81 9.4 9 8.07	1.74 0.7 0.93	21.6 8.7 11.5	Seed inoculation
Candido et al. (2020)	Brazil	Typic Hapludox	*Bradyrhizobium japonicum* *Azospirillum brasilense* Control	8.6 8.81 7.2	1.4 1.61	19.4 22.4	-
Salman and Al-Shibani (2020).	Iraq	Silt Clay Loam	*Bacillus* bacteria Trichoderma fungus Control	6 6.1 5.7	0.3 0.4	5.2 7.0	-

Table 1 (continued)

Reference	Country	Soil type (experimental site)	Treatment	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Balbinot et al. (2020)	Brazil	Cambissolo Háplico(Inceptisols)	Without inoculation and top-dressing of 50 % of the required N Without inoculation and top-dressing of 100 % of the required N *Bacillus sp*. EB02 isolate inoculation *Bacillus sp*. EB16 isolate inoculation *Bacillus sp*. EB12 isolate inoculation *Bacillus sp*. EB23 isolate inoculation *Bacillus sp*. EB14 isolate inoculation Control without fertilization or inoculation	9.21 11.85 9.84 9.84 7.9 8.46 7.55 7.42	1.79 4.43 2.42 2.42 0.48 1.04 0.13	24.1 59.7 32.6 32.6 6.5 14.0 1.8	Seed inoculation
Tejada et al. (2018)	Spain	Classification unspecified (physco-chemical properties detailed)	Chicken feather biostimulant levels 3.6lha-1 7.2 lha-1 Control (300 kg N ha^{-1} (as urea), 80 kg P ha^{-1} +41.7 kg N ha^{-1} [as $(NH_4)H_2PO_4$] and 120 kg K ha^{-1} as K_2SO_4) - common practice	15.52 16.48 14.17	1.35 2.31	9.5 16.3	Foliar
Di Salvo et al. (2018)	Argentina	Norumbega silty loam (Entic Hapludoll)	Commercial *Azospirillum brasilense* and *Pseudomona fluorescens* *Azospirillum brasilense strain* 40M (GenBank accession number HM002661) *Azospirillum brasilense strain 42M* (GenBank accession number HM002662) *Azospirillum brasilense strain* 40M + A. brasilense strain 42M control	10.59 10.54 10.6 11 10	0.59 0.54 0.6 1	5.9 5.4 6 10	Foliar
Ghorchiani et al. (2018)	Iran	Clay loam	*Pseudomonas fluorescens* AM fungus – *Funneliformis mosseae* *Pseudomonas fluorescens* and *Funneliformi mosseae* No inoculation or control NB: The study was under drought stress (no rainy received during the whole experimental study)	7.3 8 8.8 6.7	0.6 1.3 2.1	8.9 19.4 31.3	Seed inoculation

Table 1 (continued)

Reference	Country	Soil type (experimental site)	Treatment	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Mandic et al. (2018)	Serbia	Calcareous chernozem	*Azotobacter chroococum* + *Azotobacter vinelandii* + *Bacillus megaterium* control	13.67 11.57	2.1	18.2	Seed inoculation
Atta et al. (2017)	Egypt	Clay loam	VIUSID agro biostimulant 0.96 lha^{-1} 1.44 lha^{-1} 2lha^{-1} Control	9.12 7.1 5.99 7.46	1.66 -0.36 -1.47	22.3 -4.9 -19.7	Foliar
Hussain et al. (2019)	Pakistan	Sandy loam	*Alcaligenes sp.* AZ9 bacteria Humic acid (24.7kgha^{-1}) Control	9.1 9.9 9.0	0.1 9.9	1.1 10	Soil
Szczepanek and Wilczewski (2016)	Poland	Typic Hapludalfs	Humic preparation (Humistar) (40 dm^3 ha^{-1}) Foliar fertiliser (Drakar) (2 dm^3 ha^{-1}) Humistar (40 dm3 ha-1) + Drakar (2 dm^3 ha^{-1}) control NB: NB: Humistar contains 12% of humic acids and 3% of fulvic acids	10.42 10.28 10.23 10.0	0.42 0.28 0.23	4.2 2.8 2.3	Soil Foliar
Layek et al. (2016)	India	Sandy loam	*Kappaphycus alvarezii sap* (K) and *Gracilaria edulis* sap (G) K sap 5% at 25 DAS K sap 5% at 25 and 50 DAS K sap 5% at 25, 50 and 75 DAS K sap 10% at 25 DAS K sap 10% at 25 and 50 DAS K sap 10% at 25, 50 and 75 DAS G sap 5% at 25 DAS G sap 5% at 25 and 50 DAS G sap 5% at 25, 50 and 75 DAS G sap 10% at 25 DAS G sap 10% at 25 and 50 DAS G sap 10% at 25, 50 and 75 DAS Control (water spray)	4.18 4.28 4.45 4.35 4.65 4.78 4.11 4.29 4.59 4.46 4.76 4.9 4.1	0.08 0.18 0.35 0.25 0.55 0.68 0.01 0.19 0.49 0.36 0.66 0.8	1.95 4.3 8.5 6.1 13.4 16.6 0.2 4.6 12.0 8.8 16.1 19.5	Foliar
Nkebiwe et al.(2016)	Germany	Haplic luvisol	*Pseudomonas sp.* DSMZ 13134 *Bacillus amyloliquefaciens* FZB42 Control	7.35 7.74 7.19	0.16 0.55	2.2 7.0	Soil

Table 1 (continued)

Reference	Country	Soil type (experimental site)	Treatment	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Viruel et al. (2014)	Argentina	Silt loam	Phosphate solubilizing bacteria Uninoculated seeds + triple superphosphate (TSP) (50 kg P ha^{-1}) Inoculated with *Pseudomonas tolaasii* *Pseudomonas tolaasii* + TSP (50 kg P ha^{-1}) Uninoculated seeds	9.9 11.8 9.9 8.18	1.72 3.62 1.72	21.0 44.3 21.0	Soil Seed inoculation
Kaur and Reddy (2013)	India	-	*Pantoea cypripedii* *Pseudomonas plecoglossicida* Control	6.61 6.66 5.66	0.95 1.0	16.8 17.7	Soil
Singh et al. (2011)	India	Silty clay loam	Vesicular arbuscular mycorrhizal and *Pseudomonas striata* (Phosphorus management) *Pseudomonas striata* + *Pseudomonas striata* *Pseudomonas striata* *Glomus fasciculatum* Uninoculated	3.8 3.52 3.57 3.2	0.6 0.32 0.37	18.75 10 11.6	Seed inoculation (*Pseudomonas striata*) Soil application (*Pseudomonas striata*)
Marks et al. (2015)	Brazil	Latossolo Vermelho Distrófico (Brazilian Classification) or Typic Hapludox, (USA Soil Taxonomy) Latossolo Vermelho Eutroférrico (Brazilian classification) or Rhodic Eutrudox (USA Soil Taxonomy)	Seed inoculated (*Azospirillum*) Seed inoculated (*Azospirillum* + enriched metabolites) Leaf spray inoculation (*Azospirillum*) Leaf spray inoculation (*Azospirillum*+ enriched metabolites) Non-inoculated control NB: These are means from different sites	7.13 7.52 6.86 7.5 6.77	0.36 0.75 0.09 0.73	5.3 11.1 1.3 10.8	Seed inoculation Foliar
Charkhab et al. (2022)	Iran	Sandy loam	Treatment (biostimulants levels) 2 l ha^{-1} 4 l ha^{-1} 6 l ha^{-1} Control	6.1 8.8 8.95 5.6	0.5 3.2 3.4	8.9 57.1 60.7	-

Table 1 (continued)

Reference	Country	Soil type (experimental site)	Treatment	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Layek et al. (2015)	India	Clay loam	2.5% K-SAP	5.18	0.24	4.8	Foliar
			5% K-SAP	5.27	0.31	6.25	
			10% K-SAP	5.52	0.56	11.3	
			15% K-SAP	5.61	0.65	13.1	
			2.5% G-SAP	5.02	0.06	1.2	
			5% G-SAP	5.11	0.15	3.0	
			10% G-SAP	5.37	0.41	8.3	
			15% G-SAP	5.48	0.52	10.5	
			7.5% K-SAP + 50% RDF	3.94	-1.02	-20.6	
			Control (no sap, water spray)	4.96			
			DF (Recommended dose of fertilisers (0:60:40 kg/ha of N: P2O5:K2O)				
			Apart from the control and 7.5% K-SAP + 50% RDF, other treatments were supplied with 100% RDF				

phosphorus. The results showed that under low soil nitrogen conditions, *Sphingomonas* sp. A55 recorded the highest (12 t ha^{-1}) yield as compared to 10.2 t ha^{-1} in the control, implying 17.6% (1.8 t ha^{-1}) improvement. While under low soil phosphorus conditions, the highest yield was recorded in *Enterobacter* sp. P24 (12.3 t ha^{-1}), *Sphingomonas* sp. A55 and *Bacillus* sp. A28 with 12.1 t ha^{-1} each, compared to 10.2 t ha^{-1} in the control. This represented improvement in yield in each of the inoculants; Enterobacter sp. P24 by 20.6% (2.1 t ha^{-1}) and 18.6% (1.9 t ha^{-1}) by *Sphingomonas* sp. A55 and *Bacillus* sp. A28 respectively, compared to the control. Yield improvement was attributed to increased nitrogen and phosphorus uptake. In addition, these bacteria increased abundance of organic matter recycling bacteria while reducing nitrogen loss associated bacterial groups. Although these bacterial species were utilised through sole application, the yield effect of combining Enterobacter sp. P24, *Sphingomonas* sp. A55 and *Bacillus* sp. A28 under low and moderate soil nitrogen and phosphorus levels remains unclear.

Similarly, a study by Cunha et al. (2021) in Brazil, revealed a higher grain yield of 9.28 t ha^{-1} in *Azospirillum brasilense*, 9.78 t ha^{-1} in *Bradyrhizobium japonicum* and 8.75 t ha^{-1} in *A. brasilense* + *B. japonicum* as compared to 7.06 t ha^{-1} in the control (50% of the recommended N dose (40kg ha^{-1}). This represented an increase in grain yield by 31.4% (2.22 t ha^{-1}), 38.5% (2.72 t ha^{-1}) and 23.9% (1.69 t ha^{-1}) in *Azospirillum brasilense*, *Bradyrhizobium japonicum,* and *A. brasilense* + *B. japonicum*, respectively as compared to the control. This is a clear indication that the sole application of *Bradyrhizobium japonicum* performed better. Since a positive control with nitrogen application was used, this suggests the ability of *Bradyrhizobium japonicum* to improve yield and reduce environmental pollution by excess nitrogen application. Viruel et al. (2014) in Argentina reported a high yield of 11.8 t ha^{-1} through seed inoculation with *Pseudomonas tolaasii* compared to 9.9 t ha^{-1} in un-inoculated seeds + TSP (50 kg P ha^{-1}) and 8.18 t ha^{-1} in the control. This showed yield increment by 44.3% (3.62 t ha^{-1}) in *Pseudomonas tolaasii* compared to 21% (1.72 t ha^{-1}) in un-inoculated seeds + TSP (50 kg P ha^{-1}). Conversely, Ghorchiani et al. (2018) revealed that the combined application of *P. fluorescens* and *F. mosseae* produced a yield of 8.81 t ha^{-1}, 7.3 t ha^{-1} in *P. fluorescens*, 8.0 t ha^{-1} in *F. mosseae* compared to 6.7 t ha^{-1} in un-inoculated control under drought stress. This implies that *P. fluorescens* + *F. mosseae* slightly ameliorated drought stress signified by the highest yield increment of 31.3% (2.1 t ha^{-1}). However, earlier, the combined application of *A. brasilense* + *B. japonicum* recorded low yield as compared to sole *Bradyrhizobium japonicum.* This shows that the efficacy of microorganisms differs by their nature, mode of application and environmental stress type. The future studies should investigate the effect of combined application of *Bradyrhizobium japonicum* + *P. fluorescens*

+ *F. mosseae* under drought stress and varying soil fertility levels. It is reported that combined application increases production of phytohormones such as indole acetic acid (IAA) and enhances the availability of nutrients, especially phosphorus and nitrogen, as well as the production of secondary metabolites that ameliorate stress. Specifically, fungi enhance amelioration of drought stress by improving rhizosphere soil properties, promoting root growth, activating defense systems and reducing oxidative damage (Ghorchiani et al. 2018). However, robust field experiments are required to verify those effects due to the complex nature of soil ecosystems in different agro-environments, since the soil ecology influences the survival and viability of bioinoculants in the rhizospheric soil of maize (Anzuay et al. 2023), making their potential effect on yield under complex soil ecosystems to vary. Generally, limited research explored the role of soil ecology and agrometeorological elements in shaping the functionality of biostimulants in improving maize productivity. For this reason, it remains as one of the grey areas of research.

Categorically, Tejada et al. (2018) in Spain reported that foliar application of biostimulant from chicken feathers at the concentration of 7.2 lha^{-1} recorded the highest g yield of 16.48 t ha^{-1} compared to 14.17 t ha^{-1} in the common practice with chemical fertiliser application (control), signifying improvement by 16% (2.31 t ha^{-1}). Accordingly, Francis et al. (2016) in USA utilised different concentrations of foliar Blend® containing a complex mixture of nutrients and revealed that concentration 3.5 l ha^{-1} produced the highest yield of 14.3 t ha^{-1} compared to 13.42 t ha^{-1} in the control, revealing 6.6% (0.88 t ha^{-1}) yield increment. The improvement in yield was attributed to better plant nutrient uptake and overall improvement in plant nutrition. Meanwhile, the utilisation of *Lysobacter antibioticus* 13–6 with additives through soil application in China (Dai et al. 2023) produced yield of 12.23 t ha^{-1} compared to 10.81 t ha^{-1} in the control resulting in the improvement of grain yield by 13.4% (1.42 t ha^{-1}). Our overall synthesis reveals that chicken feather based biostimulant, foliar Blend® and *Lysobacter* antibioticus produced grain yield of over 12 t ha^{-1} each. Although, documented evidence shows that the Genus *Lysobacter* is mainly used to suppress pathogens (biocontrol), new emerging evidence shows some species of *Lysobacter* mineralises soil phosphorus. According to Dai et al. (2023), *Lysobacter antibioticus*13–6 has the potential to solubilise phosphorus and synthesise IAA. The fact that *Lysobacter antibioticus*13–6 was applied through seed coating could also suggest its ability to improve the initial establishment of seedlings. On the contrary, foliar applied biostimulants provide nutrients to maize plants at critical stages. Therefore, combining foliar Blend®, and chicken feather based biostimulant applied through foliar method with *Lysobacter antibioticus*13–6 seed inoculation could provide more insights into possibility of improving maize productivity. This could reduce reliance on agrochemicals hence making maize production sustainable.

Humic acid was the vastly studied biostimulant category. Our analysis of the studies in terms of types of soil where the experiments involving humic acids were conducted revealed varying results. A study by Szczepanek and Wilczewski (2016) in Poland under Typic Hapludalfs soil revealed that humistar (humic preparation) at 40 dm^{3} ha^{-1} had grain yield of 10.42 t ha^{-1} compared to 10.0 t ha^{-1} in the control. Accordingly, a study of the effect of different levels of humic urea under Typic Hapludalf soil in China revealed that the humic area at the 216 kg N hm^{-2} registered the highest yield of 8.5 t ha^{-1} compared to 5.4 tha^{-1} in the control (Kong et al. 2022), revealing 57.4% (3.1 tha^{-1}) improvement. The improvement was attributed to the improved soil phosphorus, nitrates and overall nutrient balance. According to Niaz et al. (2016) yield improvement by humic acid is related to hormonal processes that directly affect key physiological activities in the plant. Meanwhile, in Pakistan, Hussain et al. (2019) conducted a study under sandy loam soil and revealed grain yield of 9.9 tha^{-1} due to humic acid application at 24.7 kgha^{-1} compared to 9.0 tha^{-1} in the control, revealing 10% yield improvement. Similarly, Azeem et al. (2021) in Pakistan evaluated different humic acid doses under silty-loam soil (alkaline conditions) and revealed the yield of 3.3 t ha^{-1}, 3.64 t ha^{-1}, 3.78 t ha^{-1} and 2.76 t ha^{-1}in 1.5 kgha^{-1}, 3kgha^{-1}, 4.5 kgha^{-1} and the control, respectively. The highest yield increment of 37% (1.02 t ha^{-1}) was recorded in 4.5 kg ha^{-1} dose. Regardless of the concentrations, humic acid improves soil organic matter and nitrogen concentration and uptake by maize (Azeem et al. 2021). In addition, humic acid improves the enzymatic activity in the crop rhizosphere enhancing hydrolysation of phosphorus compounds (Purwanto et al. 2021). These processes contribute to the improvement in grain yield. Still, under silty loam soil in Pakistan, Mussarat et al. (2021) revealed grain yield of 2.76 tha^{-1} in humic acid (5 kg ha^{-1}) compared to 1.84 t ha^{-1} in the control. In Egypt, under alluvial clay soil, Abdo et al. (2022) revealed yield of 6.7 t ha^{-1}, 7.4 t ha^{-1}, 7.8 tha^{-1} and 5.9 tha^{-1} in humic acids, amino acids, humic acids + amino acids and the control, respectively. This reflects yield increment by 13.6% (0.8 t ha^{-1}), 25.4% (1.5t ha^{-1}) and 32.2% (1.9 t ha^{-1}). Critical analysis of these results reveals moderate yield improvement under typic hapludalfs, silty-loam, sandy loam and clay alluvial clay soils by different humic acid levels. Generally, the highest increment in yield by humic acid application was 57%. Overall, it became evident that the yield effect of humic acid depended on soil types and doses. Different soil types exhibit heterogeneity in soil nutrients depicting the need for precision site-specific application of equivalent doses of humic acids.

Generally, it is very important to note that in some studies, although biostimulants were used as nutrient inputs through foliar, seed or soil application, blanket application of chemical fertilisers was done to sustain the nutrient requirement of maize. This implies that research is required to develop biostimulants the solely improve maize productivity without chemical fertilisers.

3.3 Interactive Effect of Biostimulants and other Fertiliser types or Agro-inputs on Maize Grain Yield

At continental level, significant ($p<0.05$) differences in yield owing to interactive effects of biostimulants on grain yield were only observed in Asia (Fig. 3b). Based on general mapping, the highest and lowest yield was in the range of 16-20 t ha^{-1}and 1-5 t ha^{-1}, respectively (Fig. 4). Critical descriptive analysis of all articles shows that biostimulants were combined with agro-inputs including different maize genotypes, irrigation and agrochemicals such as fungicides under abiotic stresses such as drought, salinity, soil infertility, and biotic stresses. Changes in the yield effect were positive while slight reductions were also noted (Table 2).

3.3.1 Interactive Effect of Biostimulants with Irrigation and/or Water Stress, other Fertiliser Types, and Agrochemicals on Grain Yield of Maize

In terms of water management, a study by Ali et al. (2018) in Pakistan revealed that humic acid ameliorated water stress effect on grain yield. Humic acid at 20 kg ha^{-1} + 350 mm irrigation registered yield of 4.88 t ha^{-1} compared to 3.46 t ha^{-1} in the control, signifying yield improvement of 41% (1.42 t ha^{-1}). Humic acid at 20 kg ha^{-1} + 175 mm irrigation recorded yield of 4.26 t ha^{-1} compared to 3.12 t ha^{-1} in the control, revealing yield increment of 36.5% (1.14 t ha^{-1}). In Iran under irrigation withholding at staminate inflorescence appearance, humic acid at 150 ppm, 300ppm, and 450ppm had yield of 8.95, 9.48, and 9.42 t ha^{-1} compared to 8.72 t ha^{-1} in the control, respectively. Yield improved by 2.6%, 8.8% and 8.5% in 150 ppm, 300ppm, and 450ppm, respectively (Moghadam et al. 2014) as a result of improved root growth, nutrient supply, and better moisture retention. Charkhab et al. (2022) compared humic acid concentrations 2, 4 and 6 lha^{-1} under moderate and severe water stress. Yield reduced under all concentrations under both moderate and severe water stress conditions, except 6.0 lha^{-1}, which had no effect under moderate water stress. However, humic (6 lha^{-1}) acid under severe water stress reduced yield by -35.1%. Meanwhile, Nawaz et al. (2020) revealed that *Rhizobium phaseoli*-RS-1 + *Pseudomonas* spp. under normal irrigation recorded yield of 9.32 tha^{-1} compared to 5.07 t ha^{-1} in the control showing 83% yield improvement. Under terminal drought, yield was 5.4 t ha^{-1} compared to 4.5 t ha^{-1} in the control, indicating improvement by 20%. Maize yield improvement by *Rhizobium* was attributed to oxidase enzyme activity, production of exopolysaccharides and auxins and better nutrient uptake. The overall analysis of the above results shows reduced efficacy of high concentration of humic acid and application of *Rhizobium phaseoli*-RS-1 + *Pseudomonas* spp on grain yield under extreme water stress conditions.

The interaction between biostimulants and other organic and chemical fertilisers had varying effects. In China, utilisation of humic acid (3%) + control release fertiliser/urea (210 kg Nha^{-1}) produced yield of 12.7 t ha^{-1} compared to 12.1 t ha^{-1} and 6.4 t ha^{-1} in control release fertiliser and control, respectively (Guo et al. 2022). Humic acid (3%) + control release fertiliser (210 kg Nha^{-1}) had the highest yield improvement of yield of 98.4% (6.3 t ha^{-1}). Addition of humic acid to control release fertiliser improved nitrogen availability, accumulation of nitrogen in maize tissues, and consequently high nitrogen use efficiency. In addition, humic acid reduced N_2O emission by delaying nitrification and ammoniation of urea in soil. Exploring the results of Abdo et al. (2022) in Egypt involving the interaction of humic acid × amino acids× mineral and biofertiliser revealed highest yield of 9.9 t ha^{-1} in amino acids (3 g L^{-1}) + NPK 75% plus biofertilisers compared to 5.2 t ha^{-1} in the control, representing 90.4% (4.7 t ha^{-1}) improvement. However, reduction of yield by -23.9% (-2.2 t ha^{-1}) was recorded in humic acid (3 g L^{-1}) + amino acids (3 g L^{-1}) + 100% NPK. Interestingly, the earlier report showed that humic + control release fertiliser increased yield. The synthesis of these results clearly shows compatibility differences between humic acid and other biostimulants and chemical fertilisers, depicting the need for continuous investigations involving humic acids and varying combinations of other biostimulant types and/or chemical fertilisers. Contrariwise, Fall et al. (2023) in Uganda examined the interactive effect of AMF (*gigaspora, carpospore, glomus, acrospora, archaeospora, enttrophospora, and paraglomus*) with 50% and 100% NPK in different locations. The obtained results revealed that AMF + 50% NPK had the highest yield in the two locations: 6.5 t ha^{-1} in Kumi and 6.2 t ha^{-1} in Nkozi, compared to 2.7 and 2.6 t ha^{-1} in the control, respectively, revealing the yield improvement of 140.7% (3.8 t ha^{-1}) and 138.5% (3.6 t ha^{-1}). Meanwhile, AMF + 100% NPK in both locations had yield less than 4 t ha^{-1}. Accordingly, in Benin, *Glomeraceae* + 25% NPK+Urea, *Acaulosporaceae* + 25% NPK+Urea, and *Glomeraceae* + 50% NPK+Urea registered grain yield of between 3.11 – 3.19 t ha^{-1} except *Glomeraceae* + 50% NPK+Urea that produced 2.87 t ha^{-1} (Agbodjato et al. 2022). Our analysis reveals that *Acaulosporaceae* + 50% NPK+Urea slightly reduced grain yield by -1.4%, while *Glomeraceae*+25%NPK+Urea had the highest increment of yield by 13.5%. Mycorrhiza regulates growth through production of auxins and improves resistance of maize to drought and specific leaf and root pathogens. In addition, mycorrhiza *Glomeraceae* recycles nutrients and improves soil properties (Agbodjato et al. 2022), hence improving productivity (Niaz et al. 2016; Khan et al. 2019). However, from the above results, it is critical to determine the effect of integrating humic acid (3%) + control release fertiliser (urea) (210 kg

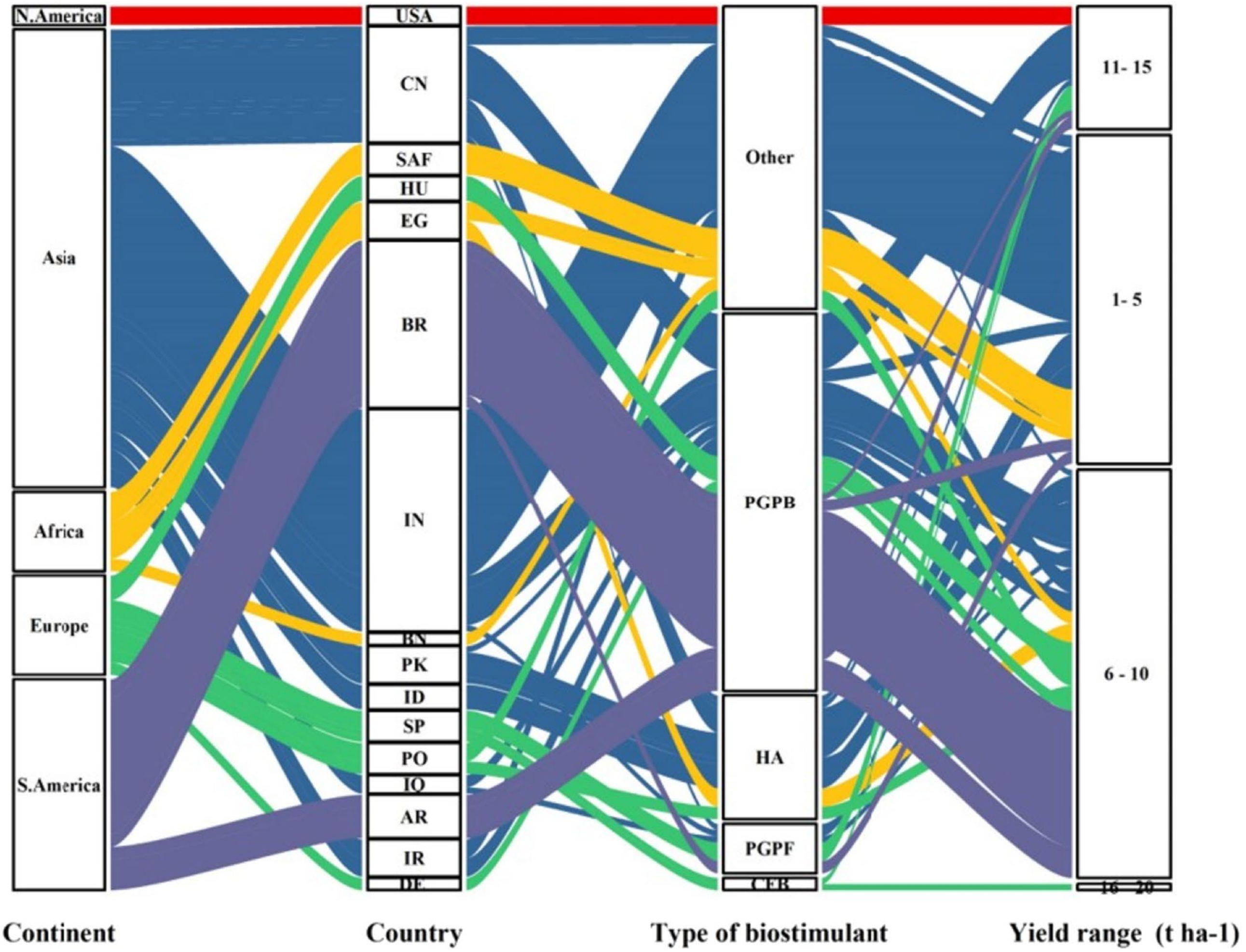


Fig. 4 Overall yield range by different biostimulants. Note:Types of biostimulants: PGPB – plant growth promoting bacteria, PGPF - plant growth promoting fungi , HA – Humic acids, CFB – Chicken feather biostimulant, Others biostimulants (seaweed extracts, phytohormones, amino acids and other ameliorants). Countries: USA – United States of America, CN – China, SAF – South Africa, HU – Hungary, EG –Egypt, , BR – Brazil, IN – India, BN – Benin, PK –Pakistan, ID – Indonesia, SP – Spain, PO – Poland, IQ – Iraq, AR – Argentina, IR – Iran, DE -German

N ha^{-1}) with *Glomus species* on grain yield. This will widen the scope of technologies available to improve grain yield while reducing soil pollution. Earlier report revealed that humic acids and amino acids reduce chemical fertilisers by 25% without yield loss (Abdo et al. 2022). Overall, in this category of interactions, humic acid (3%) in combination with chemical control release fertiliser (urea) (210 kg N ha^{-1}) had promising results.

In addition, the integration of PGPB, AMF and biochar improved grain yield. Wolna-Maruwka et al. (2021) investigated biochar × algae × mycorrhizal fungi × PGPB interactions. Biochar fertiliser + algae + mycorrhizal fungi, and biochar fertiliser + mycorrhizal fungi recorded the highest yield of 8.02 and 8.83 t ha^{-1}, respectively compared to 6.94 t ha^{-1} in the control. This indicated yield increment of 15.6% (1.08 t ha^{-1}) and 27.2% (1.89 t ha^{-1}). Accordingly, Hussain et al. (2019) investigated the effect of humic acid × PGPB × biochar × rock phosphate enriched compost. Highest yield improvements of 23.3% (2.1tha^{-1}) and 31.1% (2.8 tha^{-1}) were obtained in rock phosphate enriched compost (0.5 t ha^{-1}) + humic acid (24.7kgha^{-1}) + biochar (0.5 t ha^{-1}) + *Alcaligenes* sp. AZ9, and rock phosphate enriched compost (0.5 t ha^{-1}) + humic acid (24.7kgha^{-1}) + biochar (0.5 t ha^{-1}), respectively. What was not clear is the effect of integrating biochar (0.5 t ha^{-1}) + humic acid (24.7 kg ha^{-1}) and *Alcaligenes* sp on yield. In addition, improving soil water holding capacity, reducing nutrient leaching from the soil, absorption of soil inorganic and organic pollutants, biochar influences soil microbe diversity especially PGPB and AMF which may have either symbiotic or antagonistic interactions in the maize soil rhizosphere (Wolna-Maruwka et al. 2021). It appears that integrating biochar with *Alcaligenes* sp and/or mycorrhizal fungi sustains high grain yield. However, the doses of biochar to be combined with *Alcaligenes* sp and/

Table 2 Interactive effect of biostimulants and other fertilizer types or agro-inputs on grain yield of maize

Reference	Country	Soil type (experimental site)	Treatment details	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Tejada et al. (2016)	Spain	Classification unspecified (physico-chemical properties detailed)	AI (A0 + plus 10 Mg ha^{-1} of sewage sludge (fresh material) (7730 kgOM ha^{-1}; 9090 l ha^{-1}). A2 (A0 + plus 20 Mg ha^{-1} of sewage sludge (fresh material) (7730 kgOM ha^{-1}; 9090 l ha^{-1}). A0 - 300 kg N ha^{-1}(as urea),80 kg P ha^{-1}+ 41.7 kg N ha^{-1}[as $(NH_4)H_2PO_4$] and 120 kg K ha^{-1}(as K_2SO_4) – common practice BI - (A0 + foliar fertilised with sewage sludge at a dose of 3.6 l ha^{-1}) BS - (A0 + foliar fertilised with sewage sludge at a dose of 7.2 l ha^{-1}) BO 300 kg N ha^{-1}(as urea),80 kg P ha^{-1} + 41.7 kg N ha^{-1}[as $(NH4)H_2PO_4$] and 120 kg K ha^{-1}(as K_2SO_4) – common practice	14.20 14.22 14.13 16.00 17.01 14.13	0.07 0.09 1.87 2.88	0.5 0.6 13.2 20.4	Soil Foliar
Kaur and Reddy (2015)	India	Typic Ustifluvents, sandy loam	Phosphorus solubilizing bacteria *Pantoea cypripedii* *Pseudomonas plecoglossicida* Rock phosphate (59 kg P_2O_5 ha^{-1}) Rock phosphate (59 kg P_2O_5 ha^{-1}) + *Pantoea cypripedii* Rock phosphate (59 kg P_2O_5 ha^{-1})+ *Pseudomonas plecoglossicida* Diammonium phosphate (59 kg P_2O_5 ha^{-1}) Control	6.08 6.15 6.03 6.41 6.4 5.84 5.33	0.75 0.82 0.7 1.08 1.07 0.51	14.1 15.4 13.1 20.3 20.1 9.6	Soil (*Pantoea cypripedii*) Seed treatment for bacterial strains
Agbodjato et al. (2022)	Benin	Ferruginous soil	Mycorrhizal fungi strains × fertilizer Glomeraceae+25%NPK+Urea Acaulosporaceae+25%NPK+Urea Glomeraceae+50%NPK+Urea Acaulosporaceae+50%NPK+Urea 25%NPK+Urea 50%NPK+Urea	3.19 3.14 3.11 2.87 2.81 2.91	0.38 0.33 0.2 -0.04	13.5 11.7 6.9 -1.4	Seed coating
Guo et al. (2022)	China	Brown loam	Humic acid × control release fertilizer (CRF) CRF (210 kg N ha^{-1}) Humic acid (3%) + CRF ((210 kg Nha^{-1}) Control (without N fertilizer)	12.1 12.7 6.4	5.7 6.3	89.1 98.4	Soil
Anzuay et al. (2023)	Argentina	Typic Hapludoll	*Enterobacter* sp. J49 + half dose of phosphorus and nitrogen fertilizer [diammonium phosphate $(PO_4H(NH4)_2$ 100 kg ha^{-1}] Full dose of diammonium phosphate fertiliser [$PO_4H(NH4)_2$– 200 kg ha^{-1}] Control (without inoculation or fertilisation)	9.1 9 7.96	1.14 1.04	14.3 13.06	-
Li et al. (2013)	China	Loamy sand soil	Earthworms and AMF inoculum (*Rhizophagus intraradices*) Earthworms *Rhizophagus intraradices* inoculation Control	9.97 9.49 9.69 8.94	1.03 0.55 0.75	11.5 6.2 8.4	Soil

Table 2 (continued)

Reference	Country	Soil type (experimental site)	Treatment details	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Charkhab et al. (2022)	Iran	Sandy loam	Humic acid levels × water stress	5.61	-1.69	-23.2	-
			0 L.ha^{-1}+severe water stress	5.96	-2.04	-25.5	
			2 L.ha^{-1} +severe water stress	6.21	-2.99	-32.5	
			4 L.ha^{-1} +severe water stress	6.3	-3.4	-35.1	
			6 L.ha^{-1} +severe water stress	6.1	-1.2	-16.4	
			0 L.ha^{-1} + moderate stress	6.6	-1.4	-17.5	
			2 L.ha^{-1} + moderate stress	7.3	-1.9	-20.7	
			4 L.ha^{-1} + moderate stress	9.7	0.0	0.0	
			6 L.ha^{-1} + moderate stress	7.3			
			0 L.ha^{-1} (control)	8			
			2 L.ha^{-1} (control)	9.2			
			4 L.ha^{-1} (control)	9.7			
			6 L.ha^{-1} (control)				
Fall et al. (2023)	Uganda	Classification unspecified (physico-chemical properties detailed)	AMF × location	6.5	3.8	140.7	Soil
			AMF + 50% NPK (Kumi)	2.9	0.2	7.4	
			100% NPK (Kumi)	6.2	3.6	138.5	
			AMF + 50% NPK (Nkozi)	3.7	1.1	42.3	
			100% NPK (Nkozi)	2.7			
			Control (Kumi)	2.6			
			Control (Nkozi)				
			AMF (*Gigaspora,Carpospore,Glomus,Acrospora,Archaeospora,Enttrophospora, and Paraglomus*)				
Liu et al. (2019)	China	Aquic Inceptisol with loam texture	3.75 t ha^{-1} humic acid fertiliser and chemical fertiliser	11.6	4.4	61.1	Soil
			(81.25 kg N ha^{-1} as urea, 86.25 kg P ha^{-1}) + coastal saline soil	7.2			
			Control (100 kg N ha^{-1} as urea, 120 kg P ha^{-1} as superphosphate and 100 kg K ha^{-1})				
			NB: Humic acid composition : Humic acid and fluvic acid				
Balabanova et al. (2023)	Bulgaria	Mollic Fluvisols	Protein hydrolysates biostimulants × Herbicide	6.05	-0.42	-6.5	Foliar
			Imazamox + Trainer (2.5lha^{-1})	6.35	-0.12	-1.9	
			Imazamox + Terra - sorb (2.5lha^{-1})	6.01	-0.46	-7.1	
			Imazamox + Naturamin plus (2.5gha^{-1})	6.16	-0.31	-4.8	
			Imazamox + Naturamin WSP (0.5gha^{-1})	5.54	-0.93	-14.4	
			10 g a.i. imazamox per hectare	6.47			
			Control (untreated by imazamox)				

Table 2 (continued)

Reference	Country	Soil type (experimental site)	Treatment details	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Kalman et al. (2022)	Hungary	Classification unspecified (physco-chemical properties detailed)	PGPB × maize hybrids GKT 3213 + Micro-biological product GKT 3213 +*Bacillus pumilus* + *Pseudomonas putida* GKT 3213 + *Bacillus megaterium* + *Pseudomonas fluorescens* GKT 3213 + control GKT 3385 + Micro-biological product GKT3385+*Bacillus pumilus* + *Pseudomonas putida* GKT 3385 + *Bacillus megaterium* + *Pseudomonas fluorescens* GKT 3385 + control GKT 376 + Micro-biological product GKT376+*Bacillus pumilus* + *Pseudomonas putida* GKT 376+ *Bacillus megaterium* + *Pseudomonas fluorescens* GKT 376 + control GK Silostar + Micro-biological product GK Silostar +*Bacillus pumilus* + *Pseudomonas putida* GK Silostar + *Bacillus megaterium* + *Pseudomonas fluorescens* GK Silostar + control Micro-biological product (*Rhodopseudomonas palustris, Lactobacillus plantarum, Lacto-bacillus casei, and Saccharomyces cerevisiae*)	8.1 7.5 7.02 7.67 9.1 9.6 8.6 8.5 8.2 9.2 8.8 8.8 10.311.1 10.1 10.2	0.43 -0.17 - 0.65 0.6 1.1 0.1 -0.6 0.4 0 0.1 0.9 -0.1	5.6 -2.2 -8.5 7.1 12.9 1.2 -6.8 4.5 0 1.0 8.8 -1.0	-
Chen et al (2021a)	China	Typic-Hapli-Udic Argosol /Typic Hapludalf	Diammonium phosphate (75 kg P_2O_5 ha^{-1}) Controlled-release diammonium phosphate (75 kgP_2O_5 ha^{-1}) Diammonium phosphate (75 kg P_2O_5 ha^{-1}) + *Paecilomyces variotii* biostimulant (1.5 g ha^{-1}) Controlled diammonium phosphate (75 kg P_2O_5 ha^{-1}) + *Paecilomyces variotii* biostimulant (1.5 g ha^{-1}) Control (without P fertiliser)	10.63 11.65 11 11.5 9.93	0.7 1.72 1.07 1.75	7.5 17.3 10.8 15.8	Soil

Table 2 (continued)

Reference	Country	Soil type (experimental site)	Treatment details	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Abdo et al., (2022)	Egypt	Alluvial clay	Humic acid × Amino acid × mineral and biofertiliser Humic acid (3 g L^{-1}) + F5 Humic acid (3 g L^{-1})+ F4 Humic acids (3 g L^{-1})+ F3 Humic acid (3 g L^{-1})+ F2 Humic acid (3 g L^{-1}) + F1 Amino acid (3 g L^{-1})+ F5 Amino acid (3 g L^{-1})+ F4 Amino acid (3 g L^{-1})+ F3 Amino acid (3 g L^{-1})+ F2 Amino acid (3 g L^{-1} + F1 Humic acid (3 g L^{-1}) + Amino acids (3 g L^{-1}) + F5 Humic acid (3 g L^{-1}) + Amino acids (3 g L^{-1}) + F4 Humic acid (3 g L^{-1}) + Amino acids (3 g L^{-1}) + F3 Humic acid (3 g L^{-1}) + Amino acids (3 g L^{-1}) + F2 Humic acid (3 g L^{-1}) + Amino acids (3 g L^{-1}) + F1 Control +F5 Control +F4 Control +F3 Control +F2 Control +F1 Five rates of mineral and biofertilizer application (e.g., NPK100% (F1), NPK 75% plus biofertilizers (F2), NPK 50% plusbiofertilisers (F3), NPK 25% plus biofertilisers (F4) andbiofertilizers (F5))	4.98 6.5 6.4 7.9 7.4 5.8 7.7 7.2 9.9 6.7 6.9 7.8 7.9 9.6 6.9 5.6 4.7 4.8 5.2 9.2	0.38 1.8 1.2 2.7 -1.8 0.2 3 2.4 4.7 -2.5 1.3 3.1 3.1 4.4 -2.2	6.7 38.3 25 51.9 -19.6 3.6 63.8 50 90.4 27.2 23.2 65.9 64.6 84.6 -23.9	Foliar Seed treatment with PSB
Wolna-Maruwka et al. (2021)	Poland	Albic Luvisols (Loamy sands)	Biochar × algae × mycorrhizal fungi × PGPB Biochar fertiliser + algae + *Bacillus sp.*bacteria Biochar fertiliser + algae + mycorrhizal fungi Biochar fertiliser + Bacillus bacteria Biochar fertiliser + algae Biochar fertiliser +mycorrhizal fungi Biochar fertilizer Control NB: Biofertiliser application dose - 300 kg/ha	7.46 8.02 7.4 7.89 8.83 6.98 6.94	0.52 1.08 0.46 0.95 1.89 0.04	7.5 15.6 6.6 13.7 27.2 0.6	Soil

Table 2 (continued)

Reference	Country	Soil type (experimental site)	Treatment details	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Alves et al. (2021)	Brazil	Alfisol and Oxisol	Crop variety × season × Herbaspirillum inoculation Hybrid + dry season + Herbaspirillum Hybrid + dry season + Herbaspirillum + 40 kg N ha^{-1} Hybrid + dry season + control (not inoculated or fertilized) Hybrid + rainy season + Herbaspirillum Hybrid + rainy season + Herbaspirillum + 40 kg N ha^{-1} Hybrid + rainy season + control (not inoculated or fertilized) Variety + dry season + Herbaspirillum Variety + dry season + Herbaspirillum + 40 kg N ha^{-1} Variety + dry season + control (not inoculated or fertilized) Variety+ rainy season + Herbaspirillum Variety + rainy season + Herbaspirillum + 40 kg N ha^{-1} Variety + rainy season + control (not inoculated or fertilized)	4.9 5.9 4.8 6.3 6.6 5.9 4.8 5.4 4.9 5.1 5.4 5.1	0.1 1.1 0.4 0.7 -0.1 0.5 0 0.3	2.0 22.9 6.8 11.8 -2.0 10.2 0 5.9	Peat seed inoculation
Mussarat et al. (2021)	Pakistan	Silt loam	Humic acid + rock phosphate Humic acid + acidulated rock phosphate Humic acid + single super phosphate Humic acid + di ammonium phosphate Control Mixing ratio of phosphate sources and humic acid 90 kg P_2O_5 :5 kg HA ha^{-1}	2.62 2.84 2.81 2.78 1.84	1.07 1 0.97 0.94	58.2 54.3 52.7 51.1	Soil
de Sousa et al. (2021)	Brazil	Red Oxisol	*Bacillus* bacteria strains × triple superphosphate (TSP) B2084 + TSP B119 + TSP B116 + TSP B70 + TSP Control (non-inoculated, with TSP)	8.69 10.1 9.43 8.29 8.01	0.68 2.09 1.42 0.28	8.5 26.1 17.7 3.5	Seed coating
Araújo Guimaraes et al. (2020)	Brazil	-	Biocontrol agents × Fungicides *Bacillus subtilis* + Fungicide *Streptomyces araujoniae* + Fungicide *Bacillus subtilis* x2 *Streptomyces araujoniae* x2 Fungicide x2 Water control NB: x2 - Fungicide or microorganism sprayed twice (V9 and R1) Fungicide: (Cyproconazole + azoxystrobin)	6.1 6.6 6.1 6.4 6.2 5.5	0.6 1.1 0.6 0.9 0.7	10.9 20 10.9 16.4	Foliar

Table 2 (continued)

Reference	Country	Soil type (experimental site)	Treatment details	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
da Cunha et al. (2021)	Brazil	Dystrophic Red Yellow Argisol	Diazotrophic bacteria × cultivars *Azospirillum brasilense* + Creole corn *Bradyrhizobium japonicum* + Creole corn *A. brasilense* + *B. japonicum*+ Creole corn 100% N (80kg/ha) + Creole corn 50% N (40kg/ha) + Creole corn *Azospirillum brasilense* + Hybrid corn *Bradyrhizobium japonicum* + Hybrid corn *Azospirillum brasilense* + *Bradyrhizobium japonicum*+ Hybrid corn 100% N (80kg/ha) + Hybrid corn 50% N (40kg/ha) + Hybrid corn NB: - N doses are recommendation for the soils of Rio Grande do Sul and Santa Catarina Brazilian States -The lowest (50%N) dose is used as a control in the review	7.25 7.67 6.64 6.33 4.77 11.3 11.89 10.86 11.06 9.34	2.48 2.9 1.87 1.56 1.96 2.0 1.52 1.72	52.0 60.8 39.2 32.7 24.0 21.4 16.3 18.4	Seed inoculation
Kapela et al. (2020)	Poland	Luvisols, sandy type	Biostimulant × maize cultivar Asahi SL® (0.60 dm^3 ha^{-1}) + maize cultivar PR38N86 Asahi SL® (0.60 dm^3 ha^{-1})+ maize cultivar P8400 Zeal® (2.00 dm^3 ha^{-1})+ maize cultivar PR38N86 Zeal® (2.00 dm^3 ha^{-1})+ maize cultivar P8400 Improver® (1.00 dm^3 ha^{-1})+ maize cultivar PR38N86 Improver® (1.00 dm^3 ha^{-1}) + maize cultivar P8400 Control + maize cultivar PR38N86 Control + maize cultivar P8400	7.92 8.93 7.62 8.54 7.57 8.2 7.52 7.96	0.4 0.97 0.1 0.58 0.05 0.24	5.3 12.2 1.3 7.3 0.7 3.0	Foliar
Gavilanes et al.(2020)	Brazil	Clayey soil classified as Eutrudox (Londrina site) and as an Oxisols (Faxinal site)	*Anabaena cylindrica* and *Azospirillum brasilense* × study site *Anabaena cylindrica* and *Azospirillum brasilense* (Londrina site) *Anabaena cylindrica* (Londrina site) *Azospirillum brasilense*(Londrina site) Control(Londrina site) *Anabaena cylindrica* and *Azospirillum brasilense* (Faxinal site) *Anabaena cylindrica* (Faxinal site) *Azospirillum brasilense* (Faxinal site) Control (Faxinal site)	11.27 11.02 10.74 10.31 9.32 8.8 8.45 7.57	0.96 0.71 0.43 1.75 1.23 0.88	9.3 6.9 4.2 23.1 16.2 11.6	Seed inoculation

Table 2 (continued)

Reference	Country	Soil type (experimental site)	Treatment details	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Yousif et al. (2020)	Iraq	Loamy texture soil	Humic acid × orgnaic matter × mineral fertiliser Humic acid (4 lha^{-1}) + Mo + S0 + S1 + S2 Humic acid (8 lha^{-1}) + Mo + S0 + S1 + S2 Humic acid (4 lha^{-1}) + M1 + S0 + S1 + S2 Humic acid (8 lha^{-1}) + M1 + S0 + S1 + S2 Control (humic acid (4 lha^{-1}) + Mo + S0 + S1 + S2) Control (humic acid (8 lha^{-1}) + M1 + S0 + S1 + S2) NB:Mo - no organic matter, M1 with organic matter (25t.ha^{-1}) S0 - no mineral fertilizer, S1 50% NPK, S2 - 100% NPK	5.62 5.89 7.16 7.47 5.31 6.83	0.31 -0.94 1.85 1.09	5.8 -13.7 34.8 15.9	Foliar
Nawaz et al. (2020)	Pakistan	Clay loam (Sodic Haplocambid)	Biopriming with Rhizobium × irrigation or drought *Rhizobium phaseoli*-RS-1 + *Pseudomonas spp.* + Normal irrigation *Rhizobium phaseoli*-RS-1 + *Pseudomonas spp.* + Terminal drought Control + Normal irrigation Control + Terminal drought	9.32 5.4 5.07 4.5	4.25 0.9	83.8 20	Seed inoculation
Salman and Al-Shibani (2020)	Iraq	Silt clay loam	Biofertilizers × Potassium levels No *Bacillus* bacteria + no Trichoderma + 112.5kgha^{-1} K_2SO_4 No *Bacillus* bacteria + no Trichoderma + 225kgha^{-1} K_2SO_4 No *Bacillus* bacteria + Trichoderma + no potassium No *Bacillus* bacteria + Trichoderma + 112.5kgha^{-1} K_2SO_4 No *Bacillus* bacteria + Trichoderma + 225kgha^{-1} K_2SO_4 *Bacillus* + Trichoderma No *Bacillus* bacteria + no Trichoderma + no potassium (control) *Bacillus* bacteria + no Trichoderma + 112.5kgha^{-1} K_2SO_4 *Bacillus* bacteria + Trichoderma + 225kgha^{-1} K_2SO_4 *Bacillus* bacteria + Trichoderma + no potassium *Bacillus* bacteria + Trichoderma+ 112.5kgha^{-1} K_2SO_4 *Bacillus* bacteria + Trichoderma + 225kgha^{-1} K_2SO_4 *Bacillus* bacteria + no Trichoderma + no potassium (control)	5.8 6.0 5.8 6.3 6.67 5.8 5.73 6 6.1 6.3 6.6 9.3 5.7	0.07 0.27 0.07 0.57 0.94 0.07 0.3 0.4 0.2 0.9 3.57	1.2 4.7 1.2 9.9 16.4 1.2 5.3 7.0 3.5 15.8 62.6	-

Table 2 (continued)

Reference	Country	Soil type (experimental site)	Treatment details	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Breedt et al. (2017)	South Africa	Huttons,Arcadia, and Shortlands	Rhizobacterial strains × soil types	3.42	0.42	14	Seed inoculation
			T19 + Huttons soil	4.74	-0.31	-6.1	
			T19 + Arcadia soil	11.41	2.87	33.6	
			T19 + Shortlands soil	3.24	0.24	8.0	
			T29 + Huttons soil	4.19	-0.86	-17.0	
			T29 + Arcadia soil	11.13	2.59	30.3	
			T29 + Shortlands soil	2.97	-0.03	-1.0	
			S7 + Huttons soil	4.9	-0.15	-3.0	
			S7 + Arcadia soil	9.25	0.71	8.3	
			S7 + Shortlands soil	3.4	0.4	13.3	
			A40 + Huttons soil	4.24	-0.81	-16.0	
			A40 + Arcadia soil	8.74	0.2	2.3	
			A40+ Shortlands soil	3.6	0.6	20.0	
			A26 + Huttons soil	4.29	-0.76	-15.0	
			A26 + Arcadia soil	9.96	1.42	13.1	
			A26+ Shortlands soil	3.62	0.62	20.7	
			Brus (commercial product) + Huttons soil	4.29	0.76	15.0	
			Brus (commercial product) + Arcadia soil	9.96	1.42	16.6	
			Brus (commercial product)+ Shortlands soil	3			
			Control - Huttons soil	5.05			
			Control - Arcadia soil	8.54			
			Control – Shortlands				
Iqbal et al. (2019)	Pakistan	-	Phosphorus sources × phosphate solubilizing bacteria Low SSP (60 kg P ha $^{-1}$) +*Pseudomonas striata* High SSP (120 kg P ha^{-1}) + *Pseudomonas striata* Low poultry manure (60 kg P ha^{-1}) + *Pseudomonas striata* High poultry manure (120 kg P ha^{-1}) + *Pseudomonas striata* Low SSP (60 kg P ha^{-1}) High SSP (120 kg P ha^{-1}) Low poultry manure (60 kg P ha^{-1}) High poultry manure (120 kg P ha $^{-1}$)	5.99 6.99 5.82 6.49 5.71 6.42 5.19 5.93	0.28 0.57 0.63 0.56	4.9 8.9 12.1 9.4	Seed inoculation (*Pseudomonas striata*) SSP and poultry manure applied in the soil

Table 2 (continued)

Reference	Country	Soil type (experimental site)	Treatment details	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Atta et al. (2017)	Egypt	Clay loam	VIUSID agro biostimulant levels × maize cultivars 0.96 lha^{-1} + cultivar SC-30k9 0.96 lha^{-1} + cultivarSC-110 0.96 lha^{-1} +SC-30k8 0.96 lha^{-1} +TWC-310 0.96 lha^{-1} +Cairo-1 1.44 lha^{-1} + cultivar SC-30k9 1.44 lha^{-1} + cultivarSC-110 1.44 lha^{-1} +SC-30k8 1.44 lha^{-1} +TWC-310 1.44 lha^{-1} +Cairo-1 2 lha^{-1} + cultivar SC-30k9 2 lha^{-1}+ cultivarSC-110 2 lha^{-1} + SC-30k8 2 lha^{-1} +TWC-310 2 lha^{-1} +Cairo-1 Control (cultivar SC-30k9) Control (cultivarSC-110) Control (+SC-30k8) Control (+TWC-310) Control + (Cairo-1)	13.24 8.17 7.37 8.08 12.5 9.4 7.29 3.5 8.62 8.02 8.75 3.5 4.36 7.72 6.41 9.64 6.38 4.06 7.37 11.66	3.6 1.79 3.31 0.71 -0.24 0.91 -0.56 1.25 -3.64 0.89 -2.88 0.3 0.35 -5.25	37.3 27.6 81.5 6.1 -2.5 14.3 -13.8 17.0 -31.2 9.2 -45.1 7.4 4.7 -47.3	Foliar
Hussain et al. (2019)	Pakistan	Sandy loam	Humic acid × PGPB × biochar × rock phosphate enriched compost Rock phosphate enriched compost (RPEC) (0.5t.ha) +*Alcaligenessp*. AZ9 Humic acid (24.7kgha^{-1}) +*Alcaligenessp*.AZ9 Biochar (0.5t.ha^{-1}) +*Alcaligenessp*. AZ9 RPEC (0.5t.ha^{-1}) + Humic acid (24.7kgha^{-1}) + Biochar (0.5t.ha^{-1}) + *Alcaligenessp*. AZ9 RPEC (0.5t.ha^{-1}) + Humic acid (24.7kgha^{-1}) + Biochar (0.5t.ha^{-1}) Biochar (0.5t.ha^{-1}) RPEC (0.5t.ha^{-1}) Control	10.3 10.1 10.6 11.1 11.8 9.7 9.6 9	1.3 1.1 1.6 2.1 2.8 0.7 0.6	14.4 12.2 17.8 23.3 31.1 7.8 6.7	Soil

Table 2 (continued)

Reference	Country	Soil type (experimental site)	Treatment details	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Khan et al. (2019)	Pakistan	Silt loam	Humic acid VIUSID agro biostimulant × nitrogen × maize variety 0.6 kg HA + 0 kg N ha^{-1} + Jalal variety 1.2 kg HA + 0 kg N ha^{-1} + Jalal variety 1.8 kg HA + 0 kg N ha^{-1}+ Jalal variety 1.8 kg HA + 0 kg N ha^{-1}+ Jalal variety 0.6 kg HA + 120 kg N ha^{-1}+ Jalal variety 1.2 kg HA + 120 kg N ha^{-1}+ Jalal variety 1.8 kg HA + 120 kg N ha^{-1}+ Jalal variety Control (0 kg HA + 0 kg N ha^{-1} + Jalal variety 0.6 kg HA + 0 kg N ha^{-1} + Iqbal maize variety 1.2 kg HA + 0 kg N ha^{-1}+ Iqbal maize variety 1.8 kg HA + 0 kg N ha^{-1}+ Iqbal maize variety 1.8 kg HA + 0 kg N ha^{-1}+ Iqbal maize variety 0.6 kg HA + 120 kg N ha^{-1}+ Iqbal maize variety 1.2 kg HA + 120 kg N ha^{-1}+ Iqbal maize variety 1.8 kg HA + 120 kg N ha^{-1}+ Iqbal maize variety Control (0 kg HA + 0 kg N ha^{-1}) + Iqbal maize variety	3.1 3.22 3.34 3.94 4.19 4.47 4.74 2.54 3.21 3.33 3.52 4.06 4.31 4.56 4.82 2.94	0.56 0.68 0.8 1.4 1.65 1.93 2.2 0.27 0.39 0.58 1.12 1.37 1.62 1.88	22.0 26.8 31.5 55.1 65.0 76.0 86.6 9.2 13.3 19.7 38.1 46.6 55.1 64.0	Soil
Ali et al. (2018)	Pakistan	Calcic Cambisol	Humic acid × irrigation Humic acid at 20 kg ha^{-1} with 350 mm irrigation Humic acid at 20 kg ha^{-1} with 175 mm irrigation Control Control	4.88 4.26 3.46 3.12	1.42 1.14	41.0 36.53	Soil

Table 2 (continued)

Reference	Country	Soil type (experimental site)	Treatment details	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Niaz et al. (2016)	Pakistan	Clay loam	Humic acid × nitrogen Humic acid (5 lha^{-1}) Humic acid (5 lha^{-1}) + 150 kg $P_2O_5$5 ha^{-1} + 100 kg K2O ha-1 Humic acid (5 lha^{-1}) + 125 kg N ha^{-1} + 150 kg P_2O_5 ha^{-1} + 100 kg K_2O ha^{-1} Humic acid (5 lha^{-1}) + 150 kg N ha^{-1} + 150 kg P_2O_5 ha^{-1} + 100 kg K_2Oha^{-1} Humic acid (5 lha^{-1}) + 175 kg N ha^{-1} + 150 kg P_2O_5 ha^{-1} + 100kg K_2O ha^{-1} Humic acid (5 lha^{-1}) + 200 kg N ha^{-1} + 150 kg P_2O_5 ha^{-1} + 100kg K_2O ha^{-1} Humic acid (2.5lha^{-1}) Humic acid (2.5 lha^{-1}) + 150 kg P_2O_5 ha-1 + 100 kg K2O ha^{-1} Humic acid (2.5 lha^{-1}) + 125 kg N ha^{-1} + 150 kg P_2O_5 ha^{-1} + 100 kg K_2O ha^{-1} Humic acid (2.5 lha^{-1}) + 150 kg N ha^{-1} + 150 kg P_2O_5 ha^{-1} + 100 kg K_2Oha^{-1} Humic acid (2.5 lha^{-1}) + 175 kg N ha^{-1} + 150 kg P_2O_5 ha^{-1} + 100kg K_2O ha^{-1} Humic acid (2.5 lha^{-1}) + 200 kg N ha^{-1} + 150 kg P_2O_5 ha^{-1} + 100kg K_2O ha^{-1} No humic acid No humic acid + 150 kg P_2O_5 ha-1 + 100 kg K2O ha^{-1} No humic acid + 125 kg N ha^{-1} + 150 kg P_2O_5 ha^{-1} + 100 kg K_2O ha^{-1} No humic acid + 150 kg N ha^{-1} + 150 kg P_2O_5 ha^{-1} + 100 kg K_2Oha^{-1} No humic acid + 175 kg N ha^{-1} + 150 kg P_2O_5 ha^{-1} + 100kg K_2O ha^{-1} No humic acid + 200 kg N ha^{-1} + 150 kg P_2O_5 ha^{-1} + 100kg K_2O ha^{-1}	2.94 3.64 7.01 8.26 9.72 9.86 2.11 2.62 5.56 6.66 7.93 8.3 1.92 2.16 5.18 6.33 7.59 7.99	1.02 1.48 1.83 1.93 2.13 1.87 0.19 0.46 0.38 0.33 0.34 0.31	53.1 68.5 35.3 30.4 28.1 23.4 9.9 21.3 7.3 5.2 4.5 3.9	Soil application (irrigation water for humic acid)

Table 2 (continued)

Reference	Country	Soil type (experimental site)	Treatment details	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Singh et al. (2016)	India	Sandy loam alfisols (hyperther-mic, mixed-type Paleudtalf)	Seaweeds sap (*Kappaphycus alvarezii* (K) and *Gracilaria edulis* (G) × Recommended rate of fertilizers (RFF) 100 % RRF+2.5 % K-sap 100 % RRF+5.0 % K-sap 100 % RRF+7.5 % K-sap 100 % RRF+10 % K-sap 100 % RRF+15 % K-sap 50 % RRF+7.5 % K-sap 50 % RRF+10 % K-sap 50 % RRF+15 % K-sap 100 % RRF+2.5 % G-sap 100 % RRF+5.0 % G-sap 100 % RRF+7.5 % G-sap 100 % RRF+10 % G-sap 100 % RRF+15 % G-sap 50 % RRF+7.5 % G-sap 50 % RRF+10 % G-sap 50 % RRF+15 % G-sap 100 % RRF+water 50 % RRF+water NB: Recommended rate of fertilizers (150:60:40 kg N:P_2O_5:K_2O)	3.7 3.74 4.09 3.61 3.42 2.91 2.52 2.41 3.36 4.38 3.73 3.74 2.94 3.04 2.59 2.48 3.37 2.38	0.33 0.37 0.72 0.24 0.05 0.53 0.14 0.03 -0.01 1.01 0.37 0.37 0.43 0.24 0.21 0.1	9.8 11.0 21.4 7.1 1.5 22.3 5.9 1.3 -0.3 30.0 11.0 11.0 12.8 10.1 8.8 4.2	Foliar
Nkebiwe et al.(2016)	Germany	Haplic luvisol	Bioeffector × NH_4-Depot application method NH4-Broad + *Pseudomonas sp.* DSMZ 13134 NH4-Broad + *Bacillus amyloliquefaciens* FZB42 NH4-Broad NH4-Depot + *Pseudomonas sp.* DSMZ 13134 NH4-Depot + *Bacillus amyloliquefaciens* FZB42 NH4-Depot NB: NH_4-Depot starter MAP and subsurface placement of concentrated stabilized $(NH4)_2SO_4$ solution in water at 10 cm soil depth. MAP: Mono-ammonium phosphate (12 % NH_4-N, 22 % P)	7.23 7.05 7.23 7.41 7.36 8.35	0.0 -0.18 -0.94 -0.99	0.0 -2.5 -11.3 -11.9	Soil

Table 2 (continued)

Reference	Country	Soil type (experimental site)	Treatment details	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Ahmad et al. (2013)	Pakistan	Silty clay loam	Humic acid × NPK × FYM × *Azotobacter* NPK (120:90:60) + Humic acid (3kgha^{-1}) NPK (120:90:60) +*Azotobacter* inoculum (1.5 kgha^{-1}) NPK (60:45:30) + FYM (20 Mg ha^{-1})+ Humic acid (6kgha^{-1}) NPK (60:45:30) + FYM (20 Mg ha-1) + Humic acid (6kgha^{-1}) + *Azotobacter* inoculum (1.5 kgha^{-1}) NPK (60:45:30) + FYM (20 Mg ha^{-1}) + *Azotobacter* inoculum (1.5 kgha^{-1}) Control	2.63 2.65 2.92 3.17 3.2 1.66	0.97 0.99 1.26 1.51 1.54	58.4 59.6 75.9 91.0 92.8	Seed treatment (*Azotobacter*)
Marks et al. (2013)	Brazil	LatossoloVermelho Distrófico/ TypicHaplustox	*Azospirillum brasilense* × metabolites of *Rhizobium tropici* CIAT 899 (CM-RT1) Seed inoculated (*Azospirillum*) Seed inoculated (*Azospirillum* + enriched metabolites) Leaf spray inoculation (*Azospirillum*) Leaf spray inoculation (*Azospirillum* + enriched metabolites Non-inoculated control	7.1 7.5 6.9 7.5 6.8	0.3 0.7 0.1 0.7	4.4 10.3 1.5	Seed inoculation Foliar
Moghadam et al. (2014)	Iran	Clay loam	Humic acid levels × Irrigation levels Humic acid (150 ppm) + complete irrigation Humic acid (300 ppm) + complete irrigation Humic acid (450 ppm) + complete irrigation Humic acid (150 ppm) + irrigation withholding at 8 leaf stage Humic acid (300 ppm) + irrigation withholding at 8 leaf stage Humic acid (300 ppm) + irrigation withholding at 8 leaf stage Humic acid (150 ppm) + irrigation withholding at staminate inflorescence appearance Humic acid (300 ppm) + irrigation withholding at 8 leaf stage at staminate inflorescence appearance Humic acid (450 ppm) + irrigation withholding at 8 leaf stage at staminate inflorescence appearance Humic acid (0 ppm) + complete irrigation Humic acid (0 ppm) + Irrigation withholding at 8 leaf stage Humic acid (0 ppm) + Irrigation withholding at staminate inflorescence appearance	11.57 12.01 12.16 10.55 10.92 10.95 8.95 9.48 9.42 11.78 10.25 8.72	-0.21 0.32 0.38 0.3 0.67 0.7 0.23 0.72 0.7	-1.78 2.7 3.2 2.9 6.5 6.8 2.6 8.3 8.0	Foliar

Table 2 (continued)

Reference	Country	Soil type (experimental site)	Treatment details	Yield (t ha^{-1})	Yield change (t ha^{-1})	Yield change (% of the control)	Application method
Braccini et al. (2012)	Brazil	Red Dystrophic Argisol	Azospirillum × nitrogen × Stimulate® Without N but with *Azospirillum* Without N but with Azospirillum + Stimulate® With 50% N dose recommended for culture With 50% N dose and inoculate with *Azospirillum* 50% N dose + *Azospirillum* + Stimulate® With total N recommended for culture Total N recommended + *Azospirillum* Total N recommended + *Azospirillum* + Stimulate® Control without N and *Azospirillum* NB: Stimulate® application dose - 250 mL ha^{-1}	3.92 4.08 3.76 4.27 4.39 4.43 4.36 4.03 3.12	0.8 0.96 0.64 1.15 1.27 1.31 1.24 0.91	25.6 30.8 20.5 36.9 40.7 42.0 39.7 29.2	Seed inoculaton – (*Azospirillum*) + Foliar (Stimulate®)
Basavaraja et al. (2018)	India	Sandy loam	Seaweed *Kappaphycus alvarezii* (K sap) and *Gracilaria edulis* (G sap extracts) 2.5% K + RDF 5% K + RDF 10% K + RDF 15% K + RDF 2.5% G + RDF 5% G +RDF 10% G + RDF 15% G + RDF 7.5% K + 50% RDF Control (RDF + Water spray) NB: Three foliar sprays of both saps were applied at the rate of 2.5, 5.0, 7.5, 10, and 15.0% (v/v)	6.19 6.4 6.92 6.75 6.57 6.83 7.35 6.72 5.39 5.84	0.35 0.56 1.08 0.91 0.73 0.99 1.51 0.88 -0.45	6.0 9.6 18.5 15.6 12.5 17.0 25.9 15.1 -7.7	Foliar
Al-Temimi and Al-Hilfy (2022)	Iran	Silty loam	50% mineral fertiliser + spraying seaweed extract at 5% 50% mineral fertiliser + spraying seaweed extract at 10% 50% mineral fertiliser+ *Azotobacter chroococcum* + *Glomus mosseae* 50% mineral fertiliser + *Pseudomonas fluorescens*+ *Glomus mosseae* Control (recommended mineral fertilizer)	7.7 9.1 8.4 8 7.9	-0.2 1.2 0.5 0.1	2.5 15.1 6.3 1.3	Foliar spray (seaweed extract) Seed inoculation added as spores to the soil
Purwanto et al. (2021)	Indonesia	Classification unspecified (physco-chemical properties detailed	0 mg kg^{-1} humic acid + Phosphorus (120 mg P_2O_5 kg^{-1}) fertiliser 35 mg kg^{-1} humic acid+ Phosphorus (120 mg P_2O_5 kg^{-1}) fertiliser 75 mg kg^{-1} humic acid+ Phosphorus (120 mg P_2O_5 kg^{-1}) fertiliser 110 mg kg^{-1} humic acid+ Phosphorus (120 mg P_2O_5 kg^{-1}) fertiliser Control	4.0 4.4 4.7 3.7 0.18	3.82 4.22 4.52 3.52	2122.2 2344.4 2511.1 1955.5	-

or AMF to enhance the attainment of optimal grain yield under different soil conditions needs further investigations.

Solubilisation of phosphorus sources or fertilisers were among the key components investigated. Mussarat et al. (2021) in Pakistan revealed that mixing phosphate sources and humic acid in of 90 kg P_2O_5:5kg humic acid ha^{-1} ratio increased yield compared to the control. The yield was in 2.62 t ha^{-1} in humic acid + rock phosphate, 2.84 t ha^{-1} in humic acid + acidulated rock phosphate, 2.81 t ha^{-1} in humic acid + single super phosphate, and 2.78 t ha^{-1} in humic acid + diammonium phosphate compared to 1.84 t ha^{-1} in the control. All treatments increased yield by over 50% compared to the control. Humic acid reduced phosphorus fixation and improved its recovery in calcareous soils. In addition, combining humic acid and phosphorus sources increased soil organic matter content, phosphorus fractions and concentration, and overall phosphorus use efficiency. Conversely, in Brazil, de Sousa et al. (2021) investigated the interaction between *Bacillus* bacteria strains × triple superphosphate (TSP), and the obtained yield results were: 8.69 t ha^{-1} in B2084 TSP, 10.1t ha^{-1} in B119 + TSP, and 9.43 t ha^{-1} in B116 + TSP compared to 8.01t ha^{-1} in the control. All treatments had less than 30% yield increment, with B119 + TSP having the highest increment of 26.1% (2.09 t ha^{-1}). *Bacillus* species improves maize grain yield through production of Indole acetic acid (IAA) which improves root growth, solubilisation of phosphorus, and enhances better acquisition of phosphorus from the soil (de Sousa et al. 2021). Collectively, it seems that combining humic acid and *Bacillus* strains have potential to increase phosphorus solubilisation. Therefore, a study involving humic acid levels and *Bacillus* strains and different phosphorus sources is required. Elucidating the effect of these combinations on yield unravels the complex nature of interactions between these treatments. According to Kaur and Reddy (2015), combining phosphorus solubilising bacteria and phosphate fertilisation is a sustainable crop production technology in terms of yield increment, reduction of excessive phosphorus application and consequently profit attainment and environmental health. In fact, Ghorchiani et al. (2018) noted that inoculants such as *P. fluorescens* and *F. mosseae* can act as crude phosphorus fertilisers if directly applied to the soil in the field. Generally, bio-inoculants play a critical role in enhancing healthy and productive agro-ecosystems (Mpanga et al. (2019).

Besides, the stress induced by inappropriate application of agrochemicals such as herbicides and fungicides also affect maize yield. Incorrect application of agrochemicals such as herbicides activates multiple response mechanisms by crops that disrupt physiological processes raising concerns about their compatibility with biostimulants. Balabanova et al. (2023) investigated the interaction between protein hydrolysates biostimulants × Imazamox herbicide. The yield obtained were 6.05 t ha^{-1} in Imazamox + Trainer (2.5 lha^{-1}), 6.35 t ha^{-1} in Imazamox + Terra - sorb (2.5 lha^{-1}), 6.0 t ha^{-1} in Imazamox + Naturamin plus (2.5 g ha^{-1}), 6.16 t ha^{-1} in Imazamox + Naturamin WSP (0.5 g ha^{-1}), 5.54 t ha^{-1} in 10 g a.i. imazamox compared to 6.47 t ha^{-1} the control (untreated by imazamox). These results clearly show that the protein hydrolysates reversed the effects of Imazamox herbicide on yield. However, compared to the control, there was a slight reduction in yield, which suggests the need to utilise the protein hydrolysates in combination with other agro-inputs to boost yield. Conversely, Araújo Guimaraes et al. (2020) reported that use of fungicide followed by *Streptomyces araujoniae* or *Bacillus subtilis* had a higher yield and reduced incidence of *Fusarium verticillioides* compared to control. Yield was 6.1t ha^{-1} in *Bacillus subtilis* + fungicide, 6.6 t ha^{-1} in *Streptomyces araujoniae* + fungicide and 6.2 t ha^{-1} in fungicide compared to 5.5 t ha^{-1} in the control (water). These results indicate the ability of biostimulants to reverse stress induced by some agrochemicals. Taking these results together, a question arises, what is the effect of combining *Bacillus subtilis* and protein hydrolysates on grain yield and agrochemical stress amelioration?

Overall, excessive application of chemical fertilizers negatively affects soil health, and have phytotoxic effects. An appropriate amelioration strategy is to utilize the combination of biostimulants, other organic supplements (such as farmyard manure, poultry manure, and crop residues), and beneficial soil macro-organisms such as earthworms to optimize soil physical, chemical and microbiological properties. This reduces soil pollution, maintains soil health and sustainable crop agroecosystems. Li et al. (2013) provided evidence to this, where field inoculation with earthworms and AMF improved abundance of AMF community, nutrient uptake, and productivity of maize. However, biostimulant and organic supplements types and doses that can combine with beneficial soil macro-organisms to elicit stable optimal effects on soil health and maize productivity remains a grey area that requires research.

3.3.2 Interactive Effect of Biostimulants × Genotypes or Cultivars with Chemical Fertilizers on Grain yield of Maize

Different varieties and/or genotypes of maize respond differently to the use of biostimulants tantamounting to differences in the final yield. Kapela et al. (2020) investigated the interaction between two maize cultivars (PR38N86 and P8400) × biostimulants (Asahi SL®, Zeal® and Improver®) on yield in Poland. The highest yield (8.93 t ha^{-1}) was recorded in Asahi SL® + maize cultivar P8400 and the lowest (7.65 t ha^{-1}) in Improver® + maize cultivar PR38N86. In all biostimulants, the yield of maize cultivar P8400 was over 8 t ha^{-1}, rendering it the best performing genotype. However, because it was only applied once, it may be possible that its yield potential could be high under the three biostimulants types if applied twice or thrice under critical stages of maize growth. Equally, a study by Atta et al. (2017) on VIUSID agro biostimulant levels × maize cultivars revealed interesting results. Highest yield (13.24 t ha^{-1}) was obtained in

0.96 lha^{-1} + cultivar SC-30k9 and the lowest (3.5 t ha^{-1}) in each of the treatments; 2 lha^{-1} + cultivar SC-110 and 1.44 lha^{-1} + SC-30k8. Our analysis of yield change indicates the highest increment 81.5% (3.31 tha^{-1}) in 0.96 lha^{-1} + SC-30k8 while the highest yield reductions of -47.3% (-5.25 t ha^{-1}) in 2 lha^{-1} + Cairo-1 and -45.1% (-2.88 t ha^{-1}) in 2 lha-1 + cultivar SC-110, respectively. This shows that increasing the concentration of the biostimulant does not necessarily increase yield. Instead, the genetic constitution of the maize cultivar is a vital contributing factor. Overall, the increase and decrease in the yield depicts the need for robust field tests with several biostimulants and maize genotypes to validate their compatibility with other agro-inputs.

The productivity of maize genotypes under different biostimulants improves in combination with inorganic fertilisers. A study on the interaction between humic acid VIUSID agro biostimulant × nitrogen × maize variety in Pakistan (Khan et al. 2019) showed that 1.8 kg humic acid + 120 kg N ha^{-1}+ Jalal variety had the highest yield of 4.74 tha^{-1} compared to 2.54 t ha^{-1} in the control, revealing yield improvement by 86.6% (2.2 t ha^{-1}). Likewise, for the Iqbal maize variety, the highest yield of 4.82 t ha^{-1} was recorded in the case of applying 1.8 kg humic acid + 120 kg N ha^{-1} compared to 2.94 t ha^{-1} in the control, presenting 64% (1.88 t ha^{-1}) yield improvement. This shows that increase in humic acid concentration boosts the interactive effect between maize genotypes and biostimulants. The concentrations used: 0.6, 1.8 1.8 kg affected yield in ascending order. Since the concentration of humic acid used was low, future studies are suggested on the slightly higher concentration of VIUSID agro biostimulant together with 120 - 150kg N ha^{-1}. This could probably reveal the optimum yield response by Jalal and Iqbal maize varieties. Also, a study by Cunha et al. (2021) involving inoculation of creole corn and hybrid corn seeds with *Azospirillum brasilense* and *Bradyrhizobium japonicum* revealed slightly a higher yield in sole application compared to combined application of the bacteria. The yield results were: 7.25 t ha^{-1} in *Azospirillum brasilense* + Creole corn, 7.67 t ha^{-1} in *Bradyrhizobium japonicum* + Creole corn and 6.64 tha^{-1} in *A. brasilense* + *B. japonicum*+ creole corn compared to 4.77 t ha^{-1} in 50% N (40 kg ha^{-1}) which was the lowest nitrogen dose recommended for Rio Grande do Sul and Santa Catarina Brazilian States soils. Meanwhile, in hybrid corn, the yield was 11.3 t ha^{-1} in *Azospirillum brasilense,* 11.89 t ha^{-1} in *Bradyrhizobium japonicum,* 10.86 t ha^{-1} in *A. brasilense* + *B. japonicum* compared to 9.34 tha^{-1} in 50% N (40 kg ha^{-1}). This indicates that co-inoculation had additive effect as opposed to synergistic effect. In this study, 100% N (80 kg ha^{-1}) had 4.77 and 11.06 tha^{-1} yield in creole corn and hybrid corn, respectively. Because the two recommended nitrogen doses produced considerable yield, future studies should consider integrating the recommended doses of nitrogen with sole and co-inoculation of the two bacterial species with more genotypes of maize. Meanwhile, a study by Alves et al. (2021) on the interaction between crop variety × season × *Herbaspirillum* inoculation on yield showed that under dry and rainy seasons, *Herbaspirillum* inoculation + nitrogen application slightly improved yield compared to sole *Herbaspirillum* inoculation. Under dry conditions, the yield was 4.9 t ha^{-1} in hybrid + dry season + *Herbaspirillum,* 5.9 tha^{-1} in hybrid + dry season + *Herbaspirillum* + 40 kg N ha^{-1}compared to 4.8 t ha^{-1} in the control. Under rainy season, the yield was 6.3 tha^{-1}in hybrid + rainy season + *Herbaspirillum*, and 6.6 t ha^{-1}in hybrid + rainy season + *Herbaspirillu*m + 40 kg N ha^{-1}compared to 5.9 tha^{-1} in the control. This shows the highest yield increment of 22.9% (1.1tha^{-1}) under dry season and 11.8% (0.7 t ha^{-1}) under rainy season, respectively in hybrid + *Herbaspirillum* + 40 kg N ha^{-1}. Similar trend was recorded for variety + *Herbaspirillum* + 40 kg N ha^{-1} both under dry and rainy season except that sole variety + *Herbaspirillum* had no effect under rainy season (zero yield increment) and reduced yield by -2% in dry season. Based on this and all interactive varietal effects above, it becomes clear that key performing treatments were: 0.96 lha^{-1} of VIUSID agro biostimulant, *Bradyrhizobium japonicum and Herbaspirillum* +40 kgN ha^{-1}. However, the following questions arise: i) What is the effect of integrating 0.96 lha^{-1} of VIUSID agro biostimulant + *Herbaspirillum*+40 kgN ha^{-1} on the yield of maize varieties or genotypes? ii) What is the effect of integrating 0.96 lha^{-1} of VIUSID agro biostimulant + *Herbaspirillum* + *Bradyrhizobium japonicum* on the yield of maize varieties or genotypes? Answering these questions could reveal the complex interaction between the different biofertilisers and maize genotypes. Earlier, it was reported that plants such as maize alter the rhizosphere microbiota through secretion of root exudates. Since exudate secretion is host specific, metabolites contained in root exudates could promote or inhibit nutrients absorption especially nitrogen (Mandic et al. 2018). Therefore, it becomes clear that the interaction between biostimulants and maize genotypes with other agro-technical inputs such as chemical fertilisers and water management regimes could yield synergistic or antagonistic effects.

3.4 Effect of Biostimulants on the Quality of Maize Grain

Biostimulants improved the protein, starch and oil content of maize grain (Table 3). Research by Niaz et al. (2016) reported grain protein content of 9.99% in 5 l ha^{-1} humid acid as compared to 8.83% in the control. According to Azeem et al. (2021), protein content of 9.5% was obtained in 1.5 kg ha^{-1} humic acid, 10.3% in 3 kg ha^{-1}, 9.8% in 4.5 kg ha^{-1} as compared to 6.6% in the control. Critical examination of these results shows improvement of protein content of maize grain in the range of between 0.3% - 3.7%. According to Niaz et al. (2016), grain protein content improvement by humic acid could be related to hormone-like processes that affect protein synthesis and other relevant physiological activities. Conversely, a report by Ördög et al. (2021) revealed that cyanobacteria (*N. piscinale*) had grain protein content of 9.4% compared to 8.2% in the control representing improvement by 1.2%. A study by Kalman et al. (2022) involving different combinations of *Rhodopseudomonas palustris, Lactobacillus plantarum, Lacto-bacillus casei, Saccharomyces cerevisiae, Bacillus pumilus* and *Pseudomonas putida* recorded grain protein content between 8.3% - 8.6%. Meanwhile, Al-Temimi and Al-Hilfy (2022) investigated the combinations of 50% mineral fertiliser with seaweed extract (5%), *Pseudomonas fluorescens*, *Glomus mosseae*, and *Azotobacter chroococcum.* All combinations had 9% protein content except 50% mineral fertiliser + *Azotobacter chroococcum* + *Glomus mosseae* that had 10.1%. At the same time, Layek et al. (2015) reported the grain protein of between 10.12% - 10.45% in seedweed, *Kappaphycus alvarezii* and *Gracilaria edulis,* sap as compared to 10.1% in the control. In addition, biostimulants made from chicken feathers and sewage sludge were also reported to improve grain protein (Tejeda et al., 2016; 2018). Gao et al. (2020) emphasised that the interaction between different biostimulants increase soil nutrient content and their availability to plants. The nutrients such as nitrogen and magnesium contribute to the improvement of amino acids, starch and protein content in maize grains. Overall, slight improvements in grain protein content were reported with humic acid, 50% mineral fertiliser + *Azotobacter chroococcum* + *Glomus mosseae*, and *Kappaphycus alvarezii* and *Gracilaria edulis* sap. Therefore, it's worthwhile to investigate the effect of combinations of these biostimulants such as humic acid + *Kappaphycus alvarezii* and/or *Gracilaria edulis* sap, 25% mineral fertiliser + *Azotobacter chroococcum* + *Glomus mosseae* + humic acid, and *Glomus mosseae* + *Kappaphycus alvarezii* sap + 25% mineral fertiliser.

In terms of the oil content of maize grain, Niaz et al. (2016) reported that humic acid improved oil concentration at different application rates. Grain oil content of 4.24% was recorded in 5 l ha^{-1} humic acid, 3.93% in 5 l ha^{-1} humic acid compared to 3.38% in the control. Conversely, Al-Temimi and Al-Hilfy (2022) investigated the combinations of 50% mineral fertiliser with seaweed extract (5%), *Pseudomonas fluorescens*, *Glomus mosseae*, and *Azotobacter chroococcum.* All combinations had oil content in the range of 3.3-3.7%. Meanwhile, Kalman et al. (2022) reported that the combination *Rhodopseudomonas palustris* + *Lactobacillus plantarum* + *Lactobacillus casei* + *Saccharomyces cerevisiae* had grain oil content of 3.9%, *Bacillus pumilus*+ *Pseudomonas putida* (4.0) and 4% in the control. Generally, our synthesis reveals limited effect of biostimulants in improving grain protein, and oil. Overall, studies show that application of biostimulants improve uptake of nutrient plants (Tejada et al. 2016, Gao et al. 2020; Ördög et al. 2021; Al-Temimi and Al-Hilfy 2022) which improves the quality attributes of maize grain. Although, the improvement of starch, protein and oil content of maize grain by different biostimulants was minimal (0.1-3.7%), the positive change is an indication of their potential to increase the quality of maize grain. However, research on how to boost their positive effect to a sustainable level is required.

4 Conclusions

The review analysed the efficacy of sole and interactive effects of biostimulants on the yield and quality of maize grain from a global perspective. The key conclusions were:

- Generally, biostimulants improved grain yield. The grain yield obtained under biostimulant application ranged from 1-20 t ha^{-1} regardless of sole or combined application. Application of *Colletotrichum tofieldiae,* foliar blend and chicken feather biostimulant had the highest (14-17 t ha^{-1}) yield under sole application while under combined application, sewage sludge × NPK, humic acid × control release urea, *Azospirillum brasilense* or *Bradyrhizobium japonicum* × maize hybrids and *Rhizophagus intraradices* × earthworms were promising treatments with the yield ranging from 10-15 t ha^{-1}.
- In some instances, humic acid and *Bacillus sp* reduced yield depending on the water stress level or maize genotypes, indicating non-unidirectional effect of some biostimulants on maize productivity.
- The effects of biostimulants on the quality of grain were minimal with all attributes improved in the range between 0.1-3.7%. In fact, biostimulants had a distinct improvement on the yield, rather than the quality of grain.
- For the case of soil application, limited research extensively profiled the role of soil ecology in shaping the functionality of biostimulants in improving maize productivity; hence remains as one of the grey areas of research.
- Overall, it appears that obtaining maximum maize productivity requires use of synergistic microbial or non-microbial biostimulants by foliar and soil application, or alternatively through integration of biostimulants with reduced chemical fertilisers, especially NPK. However, exact combinations between biostimulants, reduced chemical fertilisers and other agro-inputs that can produce consistent improvement in yield, quality of maize grain, soil health, and ensure sustainable crop agroecosystems needs further investigation.

Table 3 Effect of biostimulants on the quality of maize grain

Reference	Country	Soil type (experimental site)	Treatment	Protein (%)	Protein change (%)	Starch (%)	Starch change (%)	oil(%)	oil change(%)
Niaz et al. (2016)	Pakistan	Clay loam	Humic acid (HA) 5 l HA ha^{-1} 2.5 l HA ha^{-1} Control (without HA)	9.99 9.11 8.83	1.16 0.28	-	-	4.24 3.93 3.38	0.86 0.55
Al-Temimi and Al-Hilfy (2022)	Iran	Silty loam	50% mineral fertiliser + spraying seaweed extract at 5% 50% mineral fertiliser + spraying seaweed extract at 10% 50% mineral fertiliser+ *Azotobacter chroococcum* + *Glomus mosseae* 50% mineral fertiliser + *Pseudomonas fluorescens*+ *Glomus mosseae* Control (recommended mineral fertiliser)	9.11 10.1 9.95 9.61 9.1	0.01 1.0 0.9 0.5	-	-	3.7 3.3 3.3 3.5 3.4	0.3 -0.1 0.1 0.1
Kalman et al. (2022)	Hungary	Classification unspecified (physico-chemical properties detailed)	PGPB *Rhodopseudomonas palustris* + *Lactobacillus plantarum* + *Lacto-bacillus casei* + *Saccharomyces cerevisiae* *Bacillus pumilus* + *Pseudomonas putida* *Bacillus megaterium* + *Pseudomonas fluorescens* Control	8.3 8.6 8.2 8.5	-0.1 0.1 0.3	63.4 63.2 63.3 63.4	0.0 -0.2 -0.1	3.9 4.0 3.9 4.0	0.1 0.0 -0.1

Table 3 (continued)

Reference	Country	Soil type (experimental site)	Treatment	Protein (%)	Protein change (%)	Starch (%)	Starch change (%)	oil(%)	oil change(%)
Singh et al. (2016)	India	Sandy loam alfisols (hyperthermic, mixed-type Paleudtalf)	Seaweeds sap (*Kappaphycus alvarezii* (K) *and Gracilaria edulis* (G) × Recommended rate of fertilizers (RFF) 100 % RRF+2.5 % K-sap 100 % RRF+5.0 % K-sap 100 % RRF+7.5 % K-sap 100 % RRF+10 % K-sap 100 % RRF+15 % K-sap 50 % RRF+7.5 % K-sap 50 % RRF+10 % K-sap 50 % RRF+15 % K-sap 100 % RRF+2.5 % G-sap 100 % RRF+5.0 % G-sap 100 % RRF+7.5 % G-sap 100 % RRF+10 % G-sap 100 % RRF+15 % G-sap 50 % RRF+7.5 % G-sap 50 % RRF+10 % G-sap 50 % RRF+15 % G-sap 50 % RRF+water 100 % RRF+water NB: Recommended rate of fertilisers (150:60:40 kg N:P2O5:K2O)	10.2 11.3 13.4 11.4 10.3 11 9.6 9.6 9.3 12.9 10.7 10.9 12.1 10.7 10.9 9.4 9.4 10.2	0.0 1.1 3.2 1.2 0.1 1.6 0.2 0.2 -0.9 2.7 0.5 0.7 1.9 1.3 1.5 0.0	-	-	-	-
Ördög et al. (2021)	Hungary	Alluvial soil	Cyanobacteria (*Nostoc piscinale*) Control	9.4 8.2	1.2				
Azeem et al. (2021)	Pakistan	Silty-loam	Humic acid doses 1.5 kg ha^{-1} 3kg ha^{-1} 4.5 kg ha^{-1} Control	9.5 10.3 9.8 6.6	2.9 3.7 3.2				

Table 3 (continued)

Reference	Country	Soil type (experimental site)	Treatment	Protein (%)	Protein change (%)	Starch (%)	Starch change (%)	oil(%)	oil change(%)
Layek et al. (2015)	India	Clay loam	*Kappaphycus alvarezii sap* (K) and *Gracilaria edulis sap (G)* *2.5% K-SAP* 5% K-SAP 10% K-SAP 15% K-SAP 2.5% G-SAP 5% K-SAP 10% K-SAP 15% K-SAP 7.5% K-SAP + 50% RDF Control (no sap, water spray)	10.18 10.41 10.5 10.58 10.12 10.27 10.58 10.58 9.47 10.1	0.08 0.3 0.4 0.5 0.02 0.2 0.5 0.5 -0.6				
Gao et al. (2020)	Egypt	Clay loam	Biofertilisers × NPK 100% NPK 50% NPK Humic acid + 50% NPK Biogas slurry + Humic acid + 50% NPK Biofertilizer mixture (*Azotobacter chrococcum* + AMF + *Bacillus circulans*) + 50% NPK Biogas slurry + Biofertilisers + 50% NPK Humic acid + Biofertilisers + 50% NPK, Biogas + Humic + Biofertilisers + 50% NPK NB: AMF spores (*Glomus clarum, Glomus mosseae* and *Gigaspora margarita)*	21.1 16.1 21.45 36.95 38.2 31.15 29.9 31.8	Not calculated	-	-	-	

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Data Availability All data extracted and used for reporting are included in the article.

Declarations

Competing Interests We declare no conflict of interest.

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