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A meta-analysis of research shows that applying microbial inoculants greatly increases crop production.

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Abstract

Microbial inoculant is seen as a potential technique in sustainable agriculture systems due to the quick advancement of microbial technology. Microbial inoculants increase crop output by enhancing plant nutrient availability and reducing biotic and abiotic stressors (such as disease, salt, and drought). Large-scale adoption is hampered by the uneven field effectiveness of microbial inoculants. There is little information available on the major mechanisms behind the beneficial effects of various microbial inoculants. Therefore, in order to give direction for the creation of efficient microbiological tools from both scientific and commercial perspectives, a thorough quantitative evaluation of existing inoculants on crop performance is required. We performed a meta-analysis based on 97 peer-reviewed papers to measure the advantages of various microbial inoculants on agricultural productivity and to pinpoint the primary pathways behind increased crop yield.

KEYWORDS : PGPR, microbial inoculants, crop yield, meta-analysis, and sustainable agriculture

INTRODUCTION

In order to feed the world's growing population, raising agricultural production is one of human society's top priorities (Tian et al., 2016). The overuse of agrochemicals including pesticides, herbicides, and fertilizers is a major component of the conventional agricultural paradigm (Powlson et al., 2014). However, these farming methods are not sustainable in a number of ways, and it is difficult to boost agricultural output from a little amount of arable land. For instance, improper and excessive use of agrochemicals contaminates water, harms soil health, and creates a chemical imbalance in many ecosystems (Bindraban et al., 2015; Good & Beatty, 2011). Furthermore, gain from additional nutrient inputs is limited by structural loss in (Al-Busaidi & Said, 2013). In addition to having a detrimental effect on human health and other nontarget creatures, these chemical fertilizers and pesticides also contribute to biodiversity loss, soil acidification, and N₂O emissions (Oliveira et al., 2020). The adoption of sustainable agriculture methods, including microbiological tools, is increasingly advised to address these persistent ecological and economic difficulties (Gómez-Godínez et al., 2021; Sammauria et al., 2020). One of the most promising

methods for raising agricultural output in an environmentally friendly manner is the use of microbial inoculants. Certain plant growth-promoting rhizobacteria (PGPR) assist plants primarily via two mechanisms: (i) increasing the availability of nutrients for plants and (ii) reducing biotic and abiotic stressors on plants (Etesami, 2018). N-fixation, phosphate solubilization, production of 1-aminocyclopropane-1-carboxylate (ACC) deaminase and

antimicrobial compounds, production of phytohormones, scavenging of reactive oxygen species (ROS), preservation of ion homeostasis, and stimulation of induced systemic resistance (ISR) are just a few of the direct and indirect mechanisms that PGPR can use to deliver these benefits (Berg et al., 2014; Naylor & Coleman-Derr, 2013; L. P. Singh et al., 2011). However, there is a dearth of quantitative data about the processes (increasing plant nutrients vs. reducing plant stressors) by which microbial inoculants affect plant performance, and the outcomes of field studies have been uneven. The ways that microbial inoculants promote plant development under various circumstances varies. For instance, inoculating peppermint with triple superphosphate and phosphate-solubilizing bacteria (PSB) (*Pseudomonas putida* and *Pantoea agglomerans*) increased crop production and P-use efficiency compared to noninoculated soils in a nutrient-limited environment (Sahandi et al., 2019). PSB's effective phosphate solubilization in soil, when paired with P-fertilization, showed promise for enhancing soil P nutrition and lowering the use of chemical fertilizers (Adnan et al., 2017). Microbial inoculants may also increase a plant's tolerance to various biotic and abiotic stresses. For instance, inoculation of *Bacillus subtilis* (Bhardwaj et al., 2014; Kour et al., 2019), *Pseudomonas* sp., and *Glutamicibacter halophytocola* (Xiong et al., 2019) can promote the growth of plant seedlings under salinity and drought conditions by generating 1-aminocyclopropane-1-carboxylate (ACC) deaminase or preserving ion homeostasis. Microbial inoculants have the ability to create antimicrobial chemicals under biotic stressors, which prevent the development and infection of potentially harmful bacteria (He et al., 2020). Furthermore, beneficial microorganisms may trigger the plant immune system's ISR to fend against pests or infections (Spence et al., 2014). According to a recent meta-analysis, co-inoculation with *Bradyrhizobium* and other microbial inoculants improved soybean performance and boosted nodulation (Zeffa et al., 2020), whereas microbial inoculants were very successful in boosting plant growth under drought circumstances (Rubin et al., 2017). However, a quantitative evaluation of the various efficacy of microbial inoculants is inadequate, and the range and effects of microbial inoculants on crop production differed owing to the various mechanisms of their effects. Here, we sought to determine the processes by which microbial inoculants improve crop performance as well as the effects of these inoculants on crop growth and production. Our goal in this research was to answer the following questions: (1) How much can microbial inoculants impact crop output by enhancing plant nutrient availability or reducing stress? (2) Which microbial inoculants improve plant nutrient availability or reduce stress to increase crop yield? (3) Do crop types and growing settings (field vs greenhouse) affect the effects of microbial inoculants differently?

MATERIALS AND METHODS

We gathered information from research publications that were published between 2010 and 2020 using the databases of Google Scholar and the Institute for the Scientific Information Web of Science (Thomas Reuters). The phrases "microbial inoculants/plant growth-promoting rhizobacteria (PGPR) and stress (or nutrient/nutrition)" were included of the search approach. After removing papers having titles or abstracts unrelated to the subject, a total of 202 were kept. The following criteria were used to screen these articles: (1) studies that evaluated how microbial inoculants improved plant growth by reducing stresses (such as drought, salt, or pathogens) or increasing plant nutrient availability; (2) at least one of the means of physiological indicators, such as shoot length, shoot dry weight, root length, root dry weight, dry biomass, and yield; and (3) the identity and taxonomy of microbial inoculants. Because we only concentrate on processes related to the effects of microbial inoculants alone, articles and observations that paired inoculated microbial inoculants with other biochemical inputs such humic acids, silicon, or hormones were eliminated. Our database included 101 papers and 585 observations to evaluate the impact of microbial inoculants on plant development via several pathways (Supporting Information: Table S1).

| Data category and database construction

The first findings of the literature retrieval indicate that the microbial inoculants used in these investigations often enhanced plant development via two mechanisms: either by reducing biotic and abiotic stressors or by increasing the availability of plant nutrients. Therefore, based on their experimental settings, the study's (101 articles) findings were categorized into either the "nutrient" or the "stress" group. When available, we recorded

plant physiological indicators (nitrogen [N], phosphorus [P], potassium [K], calcium [Ca], chlorophyll [Chl], magnesium [Mg], sodium [Na], and total soluble solids [TSS]) and plant parameters (shoot length, shoot dry weight, root length, root dry weight, dry biomass or yield). We gathered data from the most intense stress treatment where citations were subjected to various stress levels. Data were taken from the last time point for investigations that were repeated and consecutive. The mean, standard deviation (SD), and sample size of the microbial inoculant treatment and the control (no microbial inoculants) were needed for each observation in the meta-analysis. Since response ratios in the meta-analysis are dimensionless, different plant parameter units were not taken into account.

| **Meta-analysis**

Using log response ratios, we determined the effect size: $\text{Ln } R = \text{Ln } (V_i/V_c)$ (Hedges et al., 1999), where V_c was the mean of no microbial inoculants treatment and V_i was the mean of microbial inoculants treatment. The formula: $\%R = 100 \times [\exp(\text{Ln } R) - 1]$ was used to convert the $\text{Ln } R$ into a percentage response. Therefore, when the values' 95% confidence interval (CI) was greater than zero, the microbial inoculants were deemed to have substantially favorable impacts on plant development. The effect size was calculated using the "escalc" function in the "metafor" package (Viechtbauer, 2010) in R 3.6.1 (Team, 2013). We performed a heterogeneity test of the data before constructing the meta-analysis models to decide whether to develop a fixed-effect model or a random-effect model. We selected the random-effect model to do the meta-analysis using the "rma.uni" function in the "metafor" R package since the heterogeneity test in our database was extremely significant ($Q = 358,454.4943$, $I^2 = 99.94\%$, $df = 571$, $p < 0.0001$) (Viechtbauer, 2010). In order to exclude certain biased publications, we also visually examined a funnel plot, which led to the inclusion of 97 papers in the meta-analysis. Next, we created meta-regression models to determine the significance of the impact with crop attributes after choosing crop type, microbial inoculant species, and experimental conditions (field and greenhouse) as moderator factors that could affect crop response to microbial inoculants. Moderators with at least two studies and five observations were chosen. Crop types were categorized into six groups based on the genus level of microbial inoculant species data: wheat, maize, rice, legumes (such as chickpea, faba bean, soybean, mungbean, runner bean, and common bean), vegetables (such as potato, tomato, okra, cabbage, cauliflower, cucumber, eggplant, lettuce, pepper, and radish), and fruits (such as strawberry). Plots were created using the "ggplot2" package (Wickham, 2016), and all statistical analyzes were carried out in R 3.6.1 (Team, 2013).

RESULT

An inoculated treatment (microbial inoculant), a control treatment (no-added microbial inoculant), and a conventional farm treatment (e.g., NPK fertilizer) under stress conditions or improved plant nutrients for dry biomass ($n = 32$), plant height ($n = 106$), shoot length ($n = 56$), shoot dry weight ($n = 103$), root length ($n = 74$), root dry weight ($n = 86$), or crop yield ($n = 120$). Furthermore, there was no discernible difference in crop production between microbial inoculants and no-added microbial inoculants in 2.56% ($n = 15$) of observations. Of the observations, 31% ($n = 179$) were made in the wild and 69% ($n = 398$) were made in a greenhouse (Figure 1; Supporting Information: Table 1). Wheat (23%, $n = 131$), vegetables (22%, $n = 122$), and legumes (21%, $n = 117$) were the top three crop categories infected with microbial inoculants. More than 2% of studies included ten different microbial inoculant species (Figure 1), with *Pseudomonas* (24%, $n = 107$), *Bacillus* (12%, $n = 154$), and *Enterobacter* (8%, $n = 33$) being the top three. Less than 2% of research utilized 26% of the species.

| **Effects of microbial inoculants on crop growth under different mechanisms**

In 65.52% ($n = 19$) of observations, there was no discernible difference in yields between the conventional farm treatment (such as the addition of NPK fertilizer) and the microbial inoculants treatment. Microbial inoculants boosted yield by 34.38% ($n = 111$) when compared to no-added microbial inoculants, however yield was 14.21% ($n = 10$) lower when compared to traditional farming techniques, according to the observation that revealed a significant difference (Figure 2). By reducing plant stressors or enhancing plant nutrients, microbial inoculant treatment improved crop shoot length, root length, shoot dry weight, root dry weight, plant height, dry biomass,

and yield when compared to noninoculants (Figure 3a). By enhancing nutrients and reducing stress, microbial inoculants increased dry biomass by 25.31% ($n = 6$) and 64.73% ($n = 25$), respectively ($p = 0.05$, Figure 3ai). However, increasing food availability raised plant height by 19.54% ($n = 59$), whereas reducing stress only increased it by 13.4% ($n = 28$) ($p = 0.305$, Figure 3aii). By reducing stress and increasing nutrient availability, microbial inoculants increased the crop's root dry weight by 45.35% ($n = 38$) and 34.69% ($n = 42$), respectively, with no discernible differences between the two pathways ($p = 0.431$, Figure 3aiii). As a result, the root length grew by 39.83% ($n = 16$) when nutrients were improved and by 72.71% ($n = 55$) when

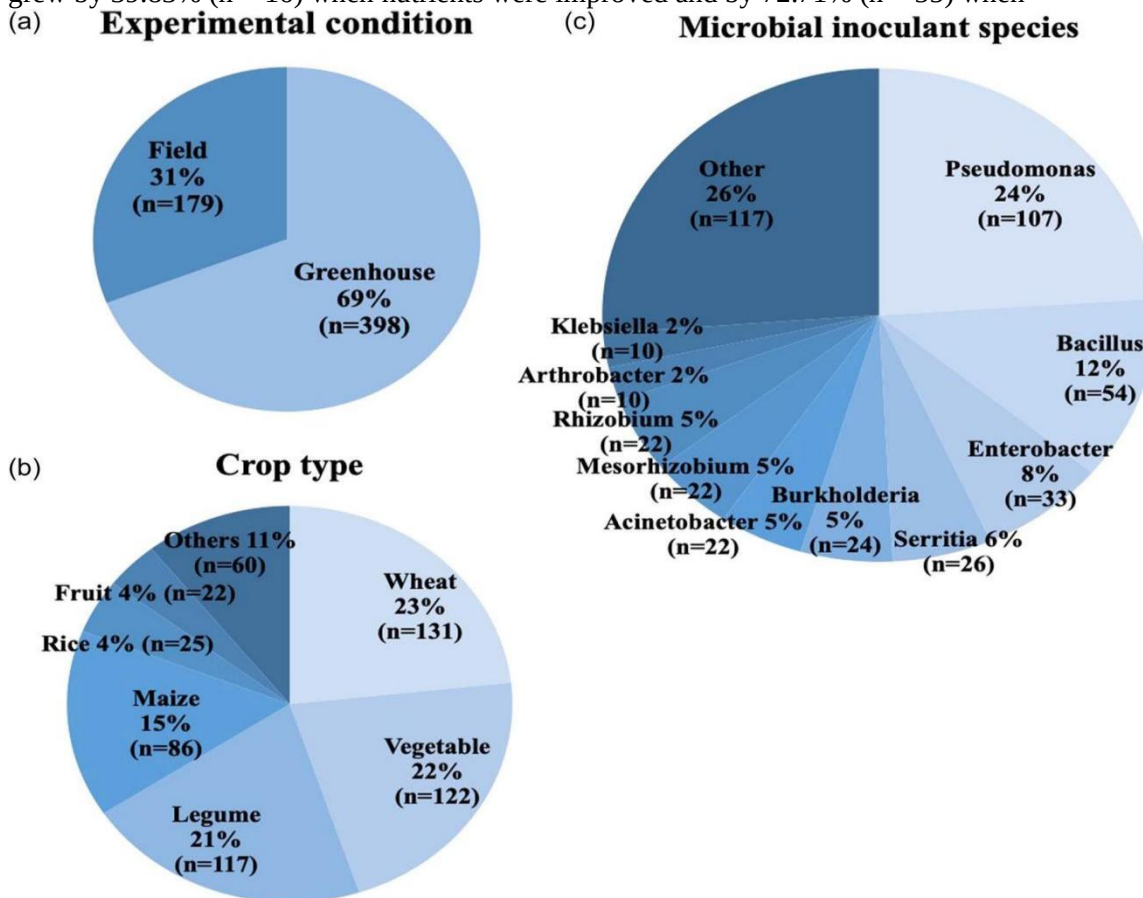


FIGURE 1 General information of meta-analysis data based on (a) experimental condition, (b) crop type and (c) microbial inoculant species.

stressors (Figure 3aiv, $p = 0.044$). By increasing nutritional availability, the shoot dry weight rose by 45.95% ($n = 48$), and by reducing stress, it increased by 51.31% ($n = 54$) ($p = 0.549$, Figure 3av). By increasing nutrient availability (30.68%, $n = 13$) and reducing stress (Figure 3avi, 46.31%, $n = 42$), microbial inoculants improved shoot length. They were more effective at reducing stress than increasing nutrients ($p = 0.017$). Improving nutrient availability (22.25%, $n = 58$) and reducing stresses (53.95%, $n = 53$) had a significant difference ($p < 0.0001$) on the effect of yield (Figure 3avii), suggesting that microbial inoculants had a greater impact on crop yield by reducing stresses than by increasing plant nutrient availability. Depending on the kind of microbial inoculant, crop output responded differently (Figure 3b). By reducing stress, *Pseudomonas* had the greatest impact on crop output (63.91%, $n = 15$), followed by *Bacillus* (26.17%, $n = 13$), *Enterobacter* (41.18%, $n = 8$), and *Mesorhizobium* (32.99%, $n = 3$). Similarly, by increasing nutrient availability, *Enterobacter* had the largest impact on crop productivity (27.12%, $n = 5$), followed by *Bacillus* (26.35%, $n = 23$), *Pseudomonas* (18.52%, $n = 6$), and *Mesorhizobium* (15.99%, $n = 4$). Microbial inoculants' effects on crop physiological indicators via several methods. According to our findings, microbial inoculants improved crop nutrient levels and had positive

effects on crop leaf physiological indicators such as N (32.81%, n = 85), P (44.81%, n = 91), K (22.49%, n = 60), and Chl (2.11%, n = 2). However, they had negative effects on crop Ca (−0.91%, n = 22) and Mg (−0.11%, n = 36) (Supporting Information: Figure S1). Similarly, cropleaf's N (18.77%, n = 51), P (44.99%, n = 47), Mg (73.98%, n = 5), Ca (39.93%, n = 6), and Chl (7.05%, n = 11) were all enhanced by microbial inoculants used to reduce stress. Furthermore, microbial inoculants used to reduce stress had a greater impact on crop leaf Ca (p = 0.02) and Mg (p < 0.0001) than those used to improve plant nutrition. Additionally, microbial inoculants improved crop grain nutrition. Following treatment with microbial inoculants, nitrogen (36.38%, n = 46), P (39.69%, n = 47), K (21.55%, n = 26), Fe (17.6%, n = 7), Zn (14.9%, n = 7), Cu (17.16%, n = 3), and Mn (27.69%, n = 3) all rose (Supporting Information: figureS2)..

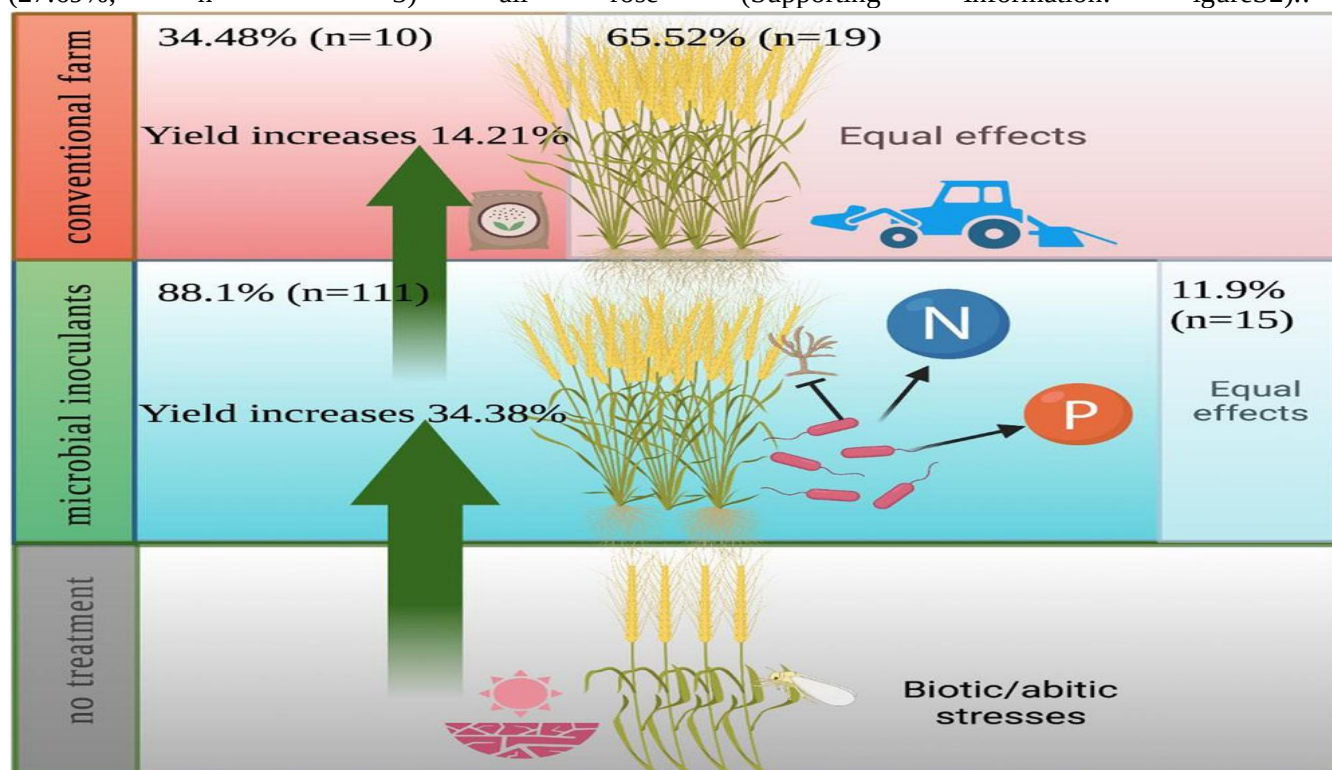


FIGURE 2 In more than 88% of observations, microbial inoculants enhanced crop output by 34.38% as compared to no treatment. Microbial inoculant and conventional practices exhibited comparable yields (identical effects) in the majority of observations (65.52%), however some observations (34.48%) showed a little improvement (14.21%) in productivity in traditional methods (such as fertilizer) as compared to microbial inoculants only treatment.

| Effects of moderator variables on crop traits

Crop type, microbial inoculant species, and experimental circumstances were among the moderator factors whose effects on crop characteristics were computed independently. The beneficial effects of microbial inoculants were comparable in terms of shoot dry weight in greenhouse and field conditions. Supporting Information: Figure S3a, 48.66% (n = 59), 44.85% (n = 12), p = 0.6844], yield [Figure 4; 30.42% (n = 45), 33.51% (n = 66), p = 0.7909], and root dry weight [Supporting Information: Figure S3b, 36.84% (n = 59), 41.98% (n = 21), p = 0.5828]. Microbial inoculant species (p < 0.0001) and crop type (p = 0.006) influenced the impact of microbial inoculant treatment on crop production (Figure 4). In particular, *Pseudomonas* sp. had the greatest impact on yield (49.94%, n = 21), followed by *Bacillus* sp. (25.66%, n = 32), *Enterobacter* sp. (27.55%, n = 13), *Mesorhizobium* sp. (15.73%, n = 7), *Acinetobacter* sp. (15.7%, n = 8), and *Serratia* sp. (14.25%, n = 8). The yield of vegetables was most significantly impacted by microbial inoculants (68.93%, n = 15), followed by

legumes (58.06%, $n = 14$), fruit (36.87%, $n = 8$), wheat (27.53%, $n = 36$), and maize (22.5%, $n = 16$). Interestingly, root and shoot responses to several microbial inoculant species were rather comparable. *Burkholderia* sp. (117.65%, $n = 6$) had the most favorable influence ($p = 0.0003$) on crop for the shoot dry weight (Supporting Information: Figure S3a). *Pseudomonas* sp. (70.01%, $n = 14$), *Rhizobium* sp. (49.91%, $n = 6$), *Mesorhizobium* sp. (31.5%, $n = 7$), and *Bacillus* sp. (27.27%, $n = 33$). Compared to rice (66.44%, $n = 6$), legumes (60.77%, $n = 30$), vegetables (46.29%, $n = 27$), and maize (25.13%, $n = 18$), wheat (72.4%, $n = 11$) reacted more strongly to microbial inoculants. *Pseudomonas* sp. showed the greatest improvement in crop performance for the root dry weight (65.39%, $n = 12$) (Supporting Information: Figure S3b), followed by *Rhizobium* sp. (43.43%, $n = 6$), *Mesorhizobium* sp. (33.52%, $n = 7$), and *Bacillus* sp. (19.47%, $n = 21$) ($p < 0.0001$). Similarly, compared to other crop types, wheat (60.54%, $n = 10$) showed the strongest response in terms of root dry weight, followed by rice (60.19%, $n = 6$), legumes (57.81%, $n = 23$), vegetables (19.42%, $n = 14$), and maize (16.08%, $n = 13$). Furthermore, the highest significant increase in root length ($p = 0.0084$) was caused by *Pseudomonas* sp. (79.9%, $n = 13$) (Supporting Information: Figure S4). Among crop types, vegetables showed the highest significant increase ($p < 0.0001$) in plant height (22.76%, $n = 20$) (Supporting Information: Figure S5).

Selecting the most effective combinations of microbial inoculants and crop categories
To determine the effect on yield promotion, nine microbial inoculant species and six crop groups were chosen. The summed effect sizes of the combinations between microbial inoculants and host crop species are displayed in Figure 5. *Burkholderia* on legume received the highest score (196.38%), followed by *Pseudomonas* and legume (86.49%), *Serratia* and vegetable (69.14%), and *Pseudomonas* and fruit (10.52%). If we exclude the literature without yield reports, the number of possible combinations was 54 (microbial inoculant species $\times$ crop species = 9×6). Only 46.29% of the combinations have been reported thus far.

DISCUSSION

Microbial inoculants promote crop yield through different mechanisms
Microbial inoculants often increase crop output by either directly improving plant nutrient availability or by reducing plant stressors such as disease, drought, and salt stress (Bakhshandeh et al., 2020; Woo & Pepe, 2018). By increasing the absorption of N, P, and K by plants, the majority of microbial inoculants with N-fixing or P- or K-solubilizing functions may increase crop output (Owen et al., 2015; Rai et al., 2020). Accordingly, our meta-analysis findings demonstrated that, as compared to a treatment without microbial inoculants, microbial inoculants increase crop production by around 22.25% by enhancing nutrients. Crop output is often positively associated with both N and chlorophyll (Agegnehu et al., 2016; Talebi, 2011). According to a number of studies, microbial inoculants boost crop productivity by boosting plant absorption of N, P, and K, which in turn increases chlorophyll and TSS (Gontia-Mishra et al., 2016; Hahm et al., 2017). This is consistent with our findings. This suggests that microbial inoculants increased the photosynthetic capability of plants and shielded the photosystem from oxidative damage (Pan et al., 2019).

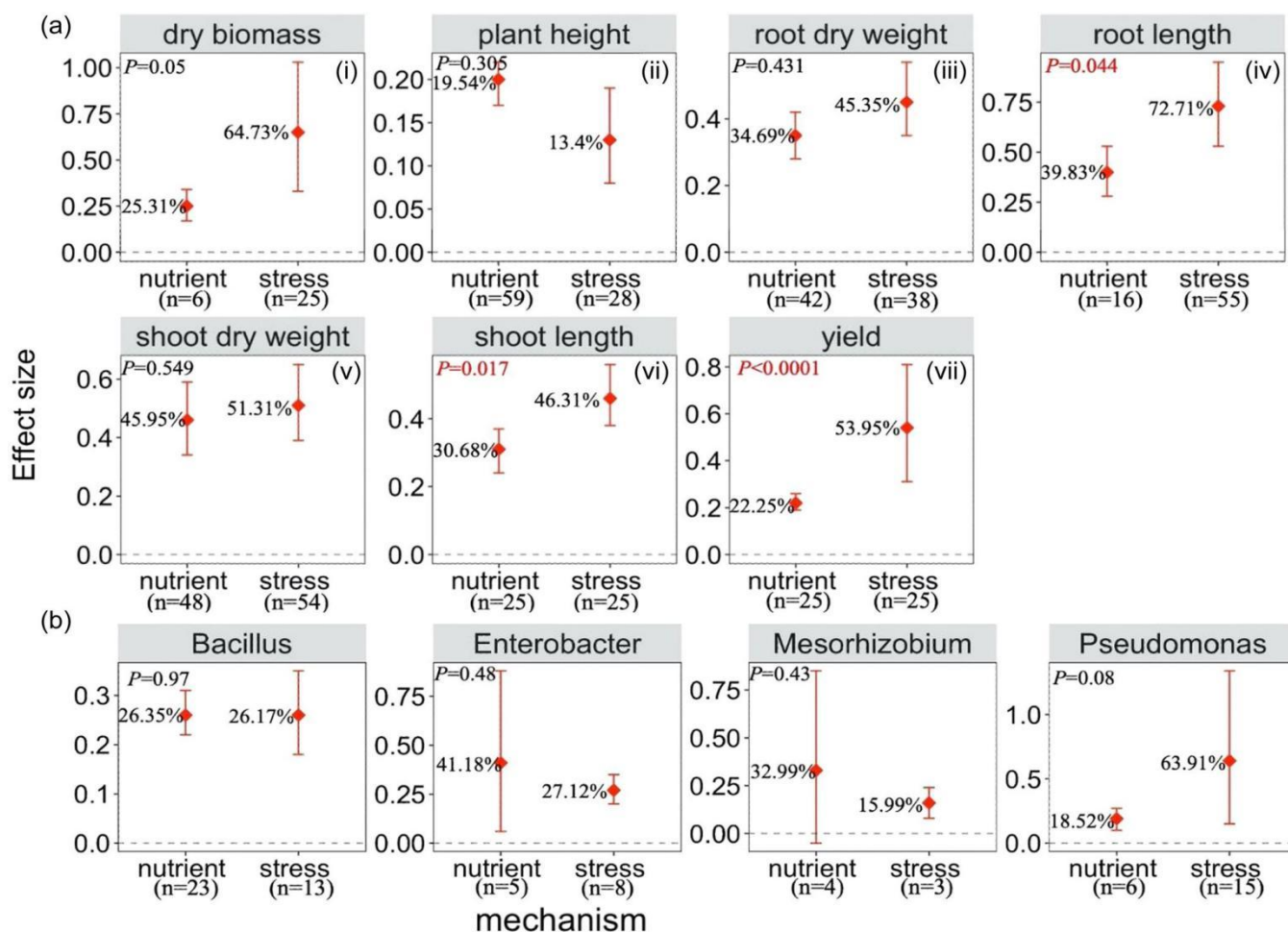
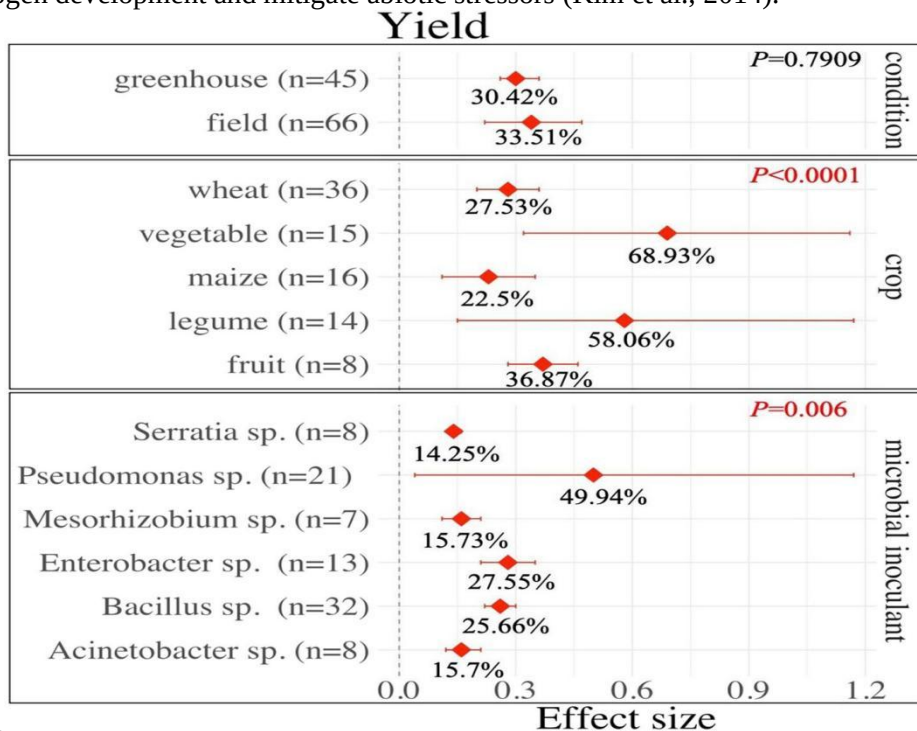


FIGURE 3 Effect size of microbial inoculants on dry biomass (i), plant height (ii), root dry weight (iii), root length (iv), shoot dry weight (v), shoot length (vi) and yield (vii) (a) and effect size of different microbial inoculant species on yield b) by enhancing nutrition and reducing stress. Error bars show $\pm 95\%$ confidence intervals, and values are means of effect sizes. A significant difference between the two groups is shown by $p < 0.05$. By generating ACC deaminase, generating antimicrobial chemicals, or inducing ISR, microbial inoculants may reduce stress and increase yield (Etesami & Maheshwari, 2018; Nadeem et al., 2010). The positive impact size on yield in the "stress" group (53.95%) shows that reducing stress is more effective on plants than increasing nutrient availability when compared to no-microbial inoculant treatment. Microbial inoculants may prevent plants from absorbing Na^+ and Ca^{2+} during salt stress, which helps maintain intracellular ion balance (Ilanguvaran & Smith, 2017). This confirms the detrimental impact of microbial inoculants on Na^+ concentration by reducing stressors.

| Inoculation performance depends on the microbial species and crop type

The benefits of *Bacillus* were comparable for both nutrient and stress groups, although *Pseudomonas* and *Enterobacter* were more effective in reducing stress than enhancing nutrition. Additionally, *Mesorhizobium* was more effective than nutrition in reducing stress. *Pseudomonas*, *Bacillus*, and *Enterobacter* species were the top three most effective microbial inoculants in our meta-analysis. The most prevalent taxa found in the rhizosphere are *Bacillus* and *Pseudomonas*, which can readily colonize and multiply in soil and on plant surfaces (Mendes et al., 2013; Sivasakthi et al., 2014). These genera often have multifunctional features that promote plant growth, such as N-fixation, P-solubilization, phytohormone synthesis (Swarnalakshmi et al., 2020), biofilm formation (Ansari & Ahmad, 2018), and the use of plant exudates as nutrients (Tan et al., 2013). As a result, *Bacillus* and *Pseudomonas* are regarded as the most potential biofertilizers in sustainable agriculture (Govindasamy et al.,

2010; Gupta et al., 2015). Another popular biofertilizer is enterobacter. It may generate IAA, siderophores, and hydrogen cyanide (HCN) (Mahdi et al., 2020), which either directly stimulate plant growth or indirectly inhibit pathogen development and mitigate abiotic stressors (Kim et al., 2014).



Thus,

FIGURE 4 Microbial inoculant effect size on yield is categorized by moderator factors, such as crop type, microbial inoculant species, and condition. Error bars show $\pm 95\%$ confidence intervals, and values are means of effect sizes. A mixed-effects multivariate regression model inside the yield data set is represented by the p value in each moderator panel (condition, microbial inoculant, or crop type).

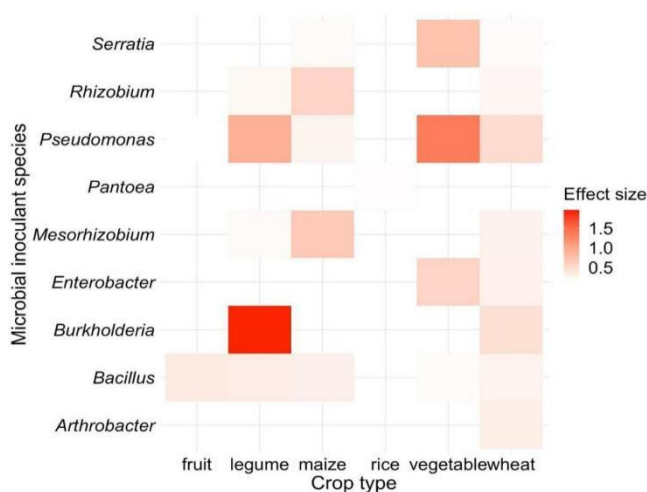


FIGURE 5 Microbial inoculant effect sizes on crop production for each combination of crop type and microbial species. *Pseudomonas*, *Bacillus*, and *Enterobacter* species are better at colonizing crop hosts than other organisms. They may also interact with microorganisms in the plant, rhizosphere, and bulk soil in both antagonistic and synergistic ways to benefit the host. Furthermore, microbial inoculants have the greatest impact on the production of legumes and vegetables, followed by fruit, wheat, and maize. Vegetable and legume crops

may benefit from a wide range of microbial inoculants from the genera *Azospirillum*, *Azotobacter*, *Pseudomonas*, *Bacillus*, *Enterobacter*, *Burkholderia*, *Serratia*, and *Rhizobium* (Bhattacharyya & Jha, 2012; Hayat et al., 2010). Helper bacteria may improve nodulation and symbiotic contact, whereas rhizobia typically survive and colonize the roots or the rhizosphere of legume plants (Swarnalakshmi et al., 2020). Furthermore, helper microorganisms may provide phytohormones and other advantages to the host (Prakamhang et al., 2015). In the future, this strategy ought to be used to increase the effectiveness of microbial inoculants.

Perspective on future studies

Numerous underlying mechanisms for microbial inoculants that promote plant growth have been identified and documented as a result of recent advancements in the use of molecular and "omics" technologies (Qin et al., 2016; Sati et al., 2022). In traditional agriculture, chemical pesticides and fertilizers are often used excessively. Crop yields would be equivalent or greater if chemical fertilizers were partially or completely replaced with microbial inoculants (Cai et al., 2015; Paungfoo-Lonhienne et al., 2019), which may directly support wholesome food and a sustainable ecosystem. Therefore, using microbial inoculants with nutrition-promoting and/or stress-relieving properties in agriculture may increase crop yields and enhance product quality. Our meta-analysis's findings indicated that crop performance improved more when stress was reduced than when nutrients were improved. These significant results imply that the usage of chemical pesticides, which have detrimental effects on the environment and biodiversity, might be decreased when combined with microbial inoculants. This implies that the first commercialization efforts should concentrate on microbial inoculants with stress-relieving characteristics. Nevertheless, only a tiny percentage of research (2.56%) found no discernible impact on crop productivity. Microbial synthetic communities, or SynComs, are created microbial communities with a variety of functional characteristics. Based on the known connection between plant phenotypes and microbiome, (Delgado-Baquerizo, 2022; Liu et al., 2022; Vorholt et al., 2017) offers a solid future route for using soil and plant microbiomes for sustainable agriculture (Trivedi et al., 2021). The effectiveness of microbial solutions to agricultural problems may be enhanced in the future by our capacity to modify the microbiome in situ through biochemical or plant breeding mechanisms and to include both microbial inoculants and helper microbes in SynComs (de Souza et al., 2020; B. K. Singh et al., 2020). Furthermore, as the effects may differ depending on the environment, there is still room for improvement when choosing the best combinations of microbial inoculants and host plant species (Lopes et al., 2021, Shah et al., 2021). For instance, it has been shown that *Burkholderia* nodules some legumes, including *Phaseolus vulgaris* and *Cyclopia* spp. (Lardi et al., 2017). A growing number of strains from the beta-Proteobacteria genus have recently been identified from legume nodules, demonstrating the prevalence and stability of *Burkholderia*-legume symbiosis (Peix et al., 2015). The key to increasing legume output is the symbiotic system, which may result in more efficacy than other combinations of microbial inoculants and plants. However, it is fundamentally challenging for meta-analysis to produce definitive evidence since our meta-analysis is based on several papers that employed a variety of study circumstances, techniques, and stress regimens. However, it offers broad patterns in the results and may be quite helpful in directing subsequent lines of inquiry.

REFERENCES

- Phosphate-solubilizing bacteria counteract the negative impact of soil calcification on phosphorus bioavailability in alkaline soils, according to Adnan M, Shah Z, Fahad S, Arif M, Alam M, Khan IA, et al. Agegnehu G, Bass AM, Nelson PN, Bird MI. *Sci Rep.* 2017; 7: 1–13. advantages of compost, biochar, and biochar-compost for greenhouse gas emissions, maize production, and soil quality in tropical agricultural soil. *Sci Total Environ.* 543:295–306, 2016.
- Al-Busaidi KT stated. Banana (*Musa* AAA cv. Malindi) growth and yield in saline and non-saline soil in Oman are affected by the addition of organic and inorganic fertilizers. *J. Hortic.* 2013; 5:146–55.
- Ansari FA, Ahmad I. *Pseudomonas entomophila* FAP1: a potential PGPR: biofilm formation, characteristics that promote plant growth, and rhizosphere colonization. *Adv Microbiol.* 2018; 8:235–51.
- Yaghoubian Y, Pirdashti H, Bakhshandeh E, and Gholamhosseini M. Under drought and salt stress, microorganisms that promote plant development may enhance soybean germination, seed-ling growth, and

potassium absorption. *Plant Growth Regulation*, 2020, 90:123–36.

Berg G, Mahnert A, Moissl-Eichinger C. Do plant-associated microorganisms improve indoor microbiomes and human health? *Microbiol Front*. 2014;5:15. Bhardwaj D, Ansari MW, Sahoo RK, Tuteja N. By enhancing soil fertility, plant tolerance, and crop yield, biofertilizers play a crucial role in sustainable agriculture. *Fact about Microb Cells*. 2014; 13:1–10. Jha DK, Bhattacharyya PN. PGPR, or plant growth-promoting rhizobacteria, are becoming more common in agriculture. *World Journal of Microbiology and Biotechnology*, 28: 1327–50, 2012. Bindraban PS, Dimkpa C, Rabbinge R, Nagarajan L, Roy A. reviewing fertilizers and fertilization techniques to enhance plant absorption of nutrients. 51:897–911 in *Biol Fertil Soils*, 2015.

Pang G, Li R, Ran W, Cai F, Chen W, Wei Z, and others. *Trichoderma harzianum* strain SQR-T037 colonization on tomato roots and its connection to soil microbiota, plant development, and nutrient availability. *Plant Soil*. 388:337–50 (2015).

From microbiome to traits: creating artificial microbial communities for enhanced crop resilience de Souza RSC, Armanhi JSL, Arruda P. *Front Plant Sci*. 11:1179, 2020.

Delgado-Baquerizo M. Reducing the intricacy of the soil microbiota to direct the creation of J Sustain Agric Environ. 2022; 1:9–15, next-generation SynComs.

Etesami H. Can plant growth-promoting rhizobacteria and silicon combine to help agricultural plants withstand biotic and abiotic stresses? *Agric. Ecosyst. Environ*. 253:98–112 (2018). <https://doi.org/10.1016/j.agee.2017.11.007> Etesami H, Maheshwari DK. Action mechanisms and possibilities for the use of plant growth promoting rhizobacteria (PGPRs) with numerous features that promote plant development in stress agriculture. *Ecotoxicol Environmental Safety*. 2018; 156:225–46.

•Romero E, Gómez-Godínez LJ, Banuelos J, Arteaga-Garibay RI. Resources and obstacles for using microbial communities in agriculture. 2021; 2:100062; *Curr Res Microb Sci*.

Gontia-Mishra I, Sapre S, Sharma A, Tiwari S. Rhizobacteria that promote plant development interact with wheat to improve drought resistance. *Plant Biol*. 18:992–1000, 2016.

Fertilizing nature: a tragedy of excess in the commons, Good AG, Beatty PH. *PLoS Biol*. 9:e1001124, 2011.

Bacillus and *Paenibacillus* spp.: potential PGPR for sustainable agriculture Govindasamy V, Senthilkumar M, Magheshwaran V, Kumar U, Bose P, Sharma V, et al. In: Editor Maheshwari DK. *microorganisms that support plant development and health*. Springer, Berlin, Heidelberg, 2010, Vol. 18, p. 333–64.

Plant growth promoting rhizobacteria (PGPR): present and future opportunities for the development of sustainable agriculture Gupta G, Parihar SS, Ahirwar NK, Snehi SK, Singh V. *Microb Biochem Technol*. 7:096–102, 2015.

Hahm M-S, Son J-S, Hwang Y-J, Kwon D-K, Ghim S-Y. Plant growth-promoting rhizobacteria alleviate salt stress in pepper (*Capsicum annum* L.) plants. *J Microbiol Biotechnol*. 2017; 27:1790–97. Hayat R, Ali S, Amara U, Khalid R, Ahmed I. A review of soil-beneficial bacteria and their function in promoting plant development. *Ann. Microbiol*.

2010; 60:579–98.

He H, Hao X, Zhou W, Shi N, Feng J, Han L. Identification of antimicrobial metabolites generated by *Actinomycete* strain A217, a possible biocontrol. *J Appl Microbiol*. 2020; 128:1143–52.

The meta-analysis of response ratios in experimental ecology, Hedges LV, Gurevitch J, Curtis PS. *Ecology*, 80:1150–56, 1999.

Plant growth-promoting rhizobacteria in reducing salt stress: a systems biology viewpoint, Ilangumaran G, Smith DL. *Front Plant Sci*. 8:1768, 2017.

Kim K, Jang Y-J, Lee S-M, Oh B-T, Chae J-C, Lee K-J. Conserved salinity sensitive factors in plants are up-regulated when *Enterobacter* sp. EJ01 alleviates salt stress in tomato and *Arabidopsis*. *Mol Cells*, 37:109–17 (2014).

Kour D, Rana KL, Kumar V, Kumar A, Yadav AN, Yadav N, et al. Drought-tolerant phosphorus-solubilizing microbes: biodiversity and bio-technological applications for reduction of drought stress in plants. Sayyed RZ, Arora NK, Reddy MS, editors. *Rhizo bacteria that support plant development for long-term stress reduction*. 2019, Vol. 12, Singapore: Springer, pp. 255–308.

Burkholderia phymatum is identified as a highly competitive β -Rhizobium in competition trials for legume

- infection by Lardi M, de Campos SB, Purtschert G, Eberl L, and Pessi G. *Front Microbiol.* 8: 1527, 2017.
- Verma JP, Liu H, Qiu Z, Ye J, Li J, and Singh BK. A bacterial synthetic community's successful colonization changes the microbial population in the soil and encourages plant development. *J. Sustain Agric Environ.* 2022, 1:30–42.
- Lopes MJdS, Dias-Filho MB, Gurgel ESC. Abiotic variables and inoculation techniques for bacteria that promote plant growth. *Front Sustain Food Syst.* 5:606454, 2021.
- Plant growth enhancement using rhizospheric halotolerant phosphate solubilizing bacteria *Bacillus licheniformis* QA1 and *Enterobacter asburiae* QF11 isolated from *Chenopodium quinoa* willd. Mahdi I, Fahsi N, Hafidi M, Allaoui A, Biskri L. *Microorganisms*, 2020, 8:948.
- Mendes R, Garbeva P, Raaijmakers JM. The importance of human pathogenic, plant pathogenic, and plant beneficial bacteria in the rhizosphere microbiome. *FEMS Microbiol Rev.* 37:634–63, 2013.
- Microbial ACC-deaminase: potential and uses for promoting salt tolerance in plants, Nadeem SM, Zahir ZA, Naveed M, Ashraf M. *CritRev Plant Sci.* 29:360–93 (2010).
- Naylor D, Coleman-Derr D. Bacterial populations linked with roots under drought stress. *Front Plant Sci.* 8:2223, 2018.
- Alves L, Woodbury LB, Miranda D, Honorio J, Stromer SB, Oliveira D. Atrazine leaching potential is determined at the field scale using electromagnetic induction technology. *Geoderma*, 2020, 375:114525.
- Owen D, Williams AP, Griffith GW, Withers PJ. Using commercial bio-inoculants to promote phosphorus acquisition and boost agricultural productivity. *Appl Soil Ecol.* 86:41–54, 2015.
- You Q, Zhang W, Wang T, Pan J, Peng F, Xue X, and others. A meta-analysis of how PGPR inoculation promotes the development of two salt-tolerant plant groupings. *Sustainability.* 2019;11:378.
- Paungfoo-Lonhienne C, Redding M, Pratt C, Wang W. Plant growth promoting rhizobacteria boost the effectiveness of fertilisers while lowering nitrogen loss. *J Environ Manage.* 233:337–41, 2019.
- Bacterial relationships with legumes, Peix A, Ramírez-Bahena MH, Velázquez E, Bedmar EJ. *Crit Rev Plant Sci.* 34:17–42, 2015.
- Pineda A, Dicke M, Pieterse CM, Pozo MJ. Beneficial microorganisms in a changing environment: do they always assist plants in controlling insects? 2013; 27:574–86; *Funct Ecol.*
- Powlson DS, Stirling CM, Jat ML, Gerard BG, Palm CA, Sanchez PA, et al. No-till agriculture has little ability to mitigate climate change. 2014; *Nat Clim Change*, 4:678–83.
- Tittabutr P, Boonkerd N, Teamtisong K, Uchiumi T, Abe M, Prakamhang J, and others. suggested various molecular interactions between PGPR coinoculated with *B. japonicum* THA6 and *Bradyrhizobium diazoefficiens* USDA110 on soybean symbiosis and its potential for field use. *Appl Soil Ecol.* 85:38–49, 2015.
- Microbially mediated plant salt tolerance and microbiome-based solutions for saline agriculture, Qin Y, Druzhinina IS, Pan X, Yuan Z. *Biotech Adv.* 34:1245–59 (2016).
- Rai PK, Singh M, Anand K, Saurabh S, Kaur T, Kour D, et al. The function and possible uses of rhizobacteria that promote plant development for sustainable agriculture. Rastegari AA, Yada AN, and Yadav N, editors. *New and upcoming advancements in bioengineering and microbial biotechnology.* Elsevier, 2020, pp. 49–60.
- Hungate BA, Rubin RL, and van Groenigen KJ. A meta-analysis shows that rhizobacteria that promote plant development are more effective under drought. *Plant Soil.* 416:309–23 (2017).
- Sahandi MS, Khalighi-Sigaroodi F, Badi HN, Mehrafarin A, and Sharifi M. enhancing peppermint's growth, phytochemical, and antioxidant qualities by using phosphate-solubilizing bacteria and using less phosphorus fertilizer. 2019 *Ind Crops Prod.* 141: 111777.
- Singh J, Jatwa TK, Kumawat S, Kumawat P, Sammauria R. Microbial inoculants: a possible instrument for agricultural production systems' sustainability. 2020; *Arch Microbiol.* 202:677–93.
- Samant M, Pandey SC, Sati D, and Pande V. recent developments in the molecular processes behind drought stress tolerance and pgpr. *J. Plant Nutr Soil Sci.* 2022:1–19.
- PGPR in agriculture: a sustainable strategy to boost climate change resistance Shah A, Nazari M, Antar M, Msimbira LA, Naamala J, Lyu D, et al. *Front Sustain Food Syst.* 5:667546, 2021.
- Crop microbiome and sustainable agriculture, Singh BK, Trivedi P, Egidi E, Macdonald CA, Delgado-Baquerizo M. *Nat Rev Microbiol.* 2020; 18: 601-602.
- Gill SS, Singh LP, and Tuteja N. figuring out how fungal symbionts contribute to plants' ability to withstand abiotic stress. *Plant Signaling Behavior*, 2011, 6: 175–91.

International Journal of Eco-Agriculture and Sustainable Technologies

Volume 1 Issue 3, 2025

Sivasakthi S, Usharani G, Saranraj P. A review of the biocontrol potential of *Bacillus subtilis* and *Pseudomonas fluorescens*, two plant growth-promoting bacteria (PGPR). Spence C, Alff E, Johnson C, Ramos C, Donofrio N, Sundaresan V, et al. Natural rhizospheric microorganisms suppress rice in Afr J Agric Res. 2014; 9:1265–77. blast infections. 2014; 14:1–17. BMC Plant Biol. The importance of plant growth-promoting rhizobacteria in grain legumes: growth promotion and crop yield Swarnalakshmi K, Yadav V, Tyagi D, Dhar DW, Kannepalli A, and Kumar S. Plants, 2020, 9: 1596.

Talebi R. Assessment of canopy temperature and chlorophyll content as markers of drought resistance in durum wheat (*Triticum durum* Desf.). Tan S, Yang C, Mei X, Shen S, Raza W, Shen Q, et al. Aust J Basic Appl Sci. 2011; 5:1457–62. The impact of tomato root exudate organic acids on *Bacillus amyloliquefaciens* T-5 rhizosphere colonization. Appl Soil Ecol. 64:15–22, 2013.

Microbial consortia: potential probiotics as plant biostimulants for sustainable agriculture, Woo SL, Pepe O. Front Plant Sci. 9: 1801, 2018.

Xiong Y-W, Gong Y, Li X-W, Chen P, Ju X-Y, Zhang C-M, et al. Natural halotolerant actinobacterium *Glutamicibacter halophytocola* KLBMP 5180 isolated from a coastal halophyte improves tomato seedling development and salt tolerance. 2019; 445:307–22. Plant Soil.

Plant growth-promoting rhizobacteria's effects on co-inoculation with *Bradyrhizobium* in soybean crops: a meta-analysis of research from 1987 to 2018 Zeffa DM, Fantin LH, Koltun A, de Oliveira AL, Nunes MP, Canteri MG, et al. PeerJ. 2020, 8:e7905.