seeds

MDPI

Review

Innovative Approaches for Engineering the Seed Microbiome to Enhance Crop Performance

Piao Yang [1,*], Ling Lu [1], Abraham Condrich [1], Gavin A. Muni [1], Sean Scranton [1], Shixiang Xu [2], Ye Xia [3] and Shuai Huang [1]

[1] Department of Molecular Genetics, College of Arts and Sciences, The Ohio State University, Columbus, OH 43210, USA; lu.3242@osu.edu (L.L.); condrich.3@buckeyemail.osu.edu (A.C.); muni.8@buckeyemail.osu.edu (G.A.M.); scranton.26@buckeyemail.osu.edu (S.S.); huang.5083@osu.edu (S.H.)
[2] Department of Chemistry and Biochemistry, College of Arts and Sciences, The Ohio State University, Columbus, OH 43210, USA; xu.4863@osu.edu
[3] Department of Plant Pathology, College of Food, Agricultural and Environmental Sciences, The Ohio State University, Columbus, OH 43210, USA; xia.374@osu.edu
* Correspondence: yang.4636@osu.edu

Abstract: Seed science is the comprehensive study of seeds. It encompasses their biology, production, technology, genetics, physiology, ecology, and applications in agriculture and conservation. Seed science has undergone transformative advancements through the integration of microbial technologies, with beneficial microorganisms emerging as critical tools for enhancing germination, seedling vigor, and crop resilience. Research demonstrates that microbial treatments improve nutrient uptake, hormonal regulation, and stress tolerance while establishing early symbiotic relationships with plants. This review synthesizes recent advances in understanding the roles of beneficial microbes in seed science, focusing on their impact on seed germination, seedling growth, and plant health. We explore the composition and transmission of seed microbiomes, highlighting the vertical transfer of microbes from parent plants to seeds and the influence of environmental factors on microbial community structure. The review also discusses innovative approaches to seed microbiome engineering. Particular attention is given to seed biopriming with plant growth-promoting bacteria (PGPB), which has shown significant potential in improving germination rates, seedling vigor, and crop productivity. Specific microbial strains, such as *Trichoderma* species and *Pseudomonas fluorescens*, are discussed with emphasis on their mechanisms of action in enhancing plant performance. The review also addresses the impact of breeding on seed microbiomes and explores emerging research directions, including the development of tailored microbial inoculants and the investigation of intracellular seed bacteria. By synthesizing these findings, this review aims to provide a comprehensive summary of the current state of seed microbiome research and its implications in seed science for sustainable agriculture.

Keywords: seed microbiome; beneficial microbes; crop performance; vertical transmission; biopriming; plant growth-promoting bacteria (PGPB); sustainable agriculture; syncoms

check for updates

Academic Editors: Aria Dolatabadian and Pedro Diaz-Vivancos

Received: 8 March 2025
Revised: 14 April 2025
Accepted: 12 May 2025
Published: 14 May 2025

Citation: Yang, P.; Lu, L.; Condrich, A.; Muni, G.A.; Scranton, S.; Xu, S.; Xia, Y.; Huang, S. Innovative Approaches for Engineering the Seed Microbiome to Enhance Crop Performance. *Seeds* **2025**, *4*, 24. https://doi.org/10.3390/seeds4020024

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The seed microbiome has emerged as a crucial frontier in agricultural research, offering promising avenues for enhancing crop performance and sustainability. Recent advances in seed science, particularly in the realm of beneficial microbes, have revealed the significant impact of seed-associated microorganisms on plant health, growth, and

productivity. These microbes—including bacteria, fungi, and cyanobacteria (photosynthetic blue-green algae)—interact with seeds through biopriming, coating, and inoculation strategies, offering sustainable alternatives to chemical inputs.

Seeds shelter diverse microbial communities, collectively termed the seed microbiome, which play vital duty in seed germination, seedling establishment, and plant development [1]. These microbial assemblages, comprising bacteria, fungi, and archaea, are unique among plant-associated microbiomes and have been shown to contain primarily beneficial microorganisms [2]. The seed microbiome serves as a critical link between plant generations, facilitating the vertical transmission of microbial resources from parent plants to offspring [3].

Seed microbiomes are shaped by both plant genetics and environmental factors and are increasingly recognized as a key target for sustainable agriculture. Recent advances have enabled the engineering of seed microbiomes through genetic modification of host plants, synthetic biology tools, and precision editing of microbial communities. These approaches include introducing beneficial microbes, designing synthetic microbial consortia, and editing microbial genes to enhance desired traits [4–6].

The importance of seed microbiomes extends beyond their role in plant development. They also contribute significantly to crop resilience against biotic and abiotic inflections, disease resistance, and overall plant fitness [2]. Furthermore, seed microbiomes have implications for grain quality and food security, making them a subject of intense research interest in recent years [1]. Studies have revealed that seed microbiomes are influenced by plant genotype, environmental factors, and developmental stages [1]. The vertical transmission of microbes from parent plants to seeds has been observed, suggesting a mechanism for passing beneficial microbes to offspring [7].

Seed-associated beneficial microbes have been shown to support seed germination, enhance seedling vigor, increase nutrient uptake, and improve plant resilience to various stresses [8]. Plant growth-promoting bacteria (PGPB) and fungi have also demonstrated their abilities to increase crop production and improve plant performance under adverse conditions [9,10]. Innovative approaches to manipulate seed microbiomes, such as the endophytic microbial introduction(EMI) [11] and synthetic microbial communities (SynComs) [12], are being developed to enhance crop performance [7]. Seed biopriming has emerged as a promising technique for enhancing crop performance, which is further detailed in Section 5. The use of beneficial seed microbes offers an environmentally friendly alternative to chemical fungicides, pesticides and fertilizers, aligning with the goals of sustainable agriculture [10]. These microorganisms can reduce the need for synthetic inputs while promoting natural disease suppression and nutrient cycling [13]. Research has identified various beneficial microbial strains, including species of *Bacillus*, *Pseudomonas*, and *Trichoderma*, which have shown auspicious results in enhancing plant growth and stress tolerance [14,15].

Despite promising advances, the application of microbial technologies in seed microbiome engineering also faces several challenges. Microbial stability and survival during storage and in the field can vary significantly, impacting efficacy. Introduced beneficial microbes may compete or interact unpredictably with native seed microbiota, potentially affecting their establishment and functional benefits. Furthermore, regulatory frameworks for microbial inoculants vary by region, complicating widespread commercial adoption. Finally, ensuring the reproducibility and consistent performance of microbial treatments across diverse environmental conditions remains a critical research priority for successful field application [16,17].

As our understanding of seed microbiomes continues to grow, so does the potential for harnessing these microbial communities to improve crop production, enhance food security, and promote sustainable agricultural practices.

2. Seed Microbiome Composition and Transmission

In general, the seed microbiome refers to the diverse community of microorganisms, including bacteria, fungi, and viruses, that inhabit seeds and play crucial roles in seed health, germination, and plant development. Plant growth-promoting bacteria and other beneficial microbes (endophytes for example) are integral components of the seed microbiome, playing vital roles in plant development and health from the earliest stages of growth. Recent research has revealed that seed microbiomes can be vertically transmitted from parent plants, influenced by host genotype, environmental conditions, and plant developmental stages [18].

Seed microbiomes, composed of bacteria, fungi, and archaea, are crucial for plant health and development. They form a unique microbial community distinct from other plant-associated microbiomes [2]. Seed microbiota composition varies widely, but most seeds share a core microbiome [19]. Individual seeds are often dominated by a single bacterial taxon (>75% of reads), with high variability between and within plants [20].

Vertical transmission of indigenous microbes from parent plants to seeds is a critical process in seed microbiome assembly. Parent seed and stem endosphere fungal and bacterial communities are key sources of progeny seed microbiomes [18]. Seed-transmitted fungi and bacteria dominate juvenile crop plant microbiomes by abundance [21]. Vertical transmission allows indigenous beneficial microbes to establish early founder populations, shaping the plant microbiome from the start through priority effects (the influence that the order and timing of species arrival have on the assembly and function of a microbial community, in other words, early-arriving microbes can shape the environment in ways that affect the success of later-arriving species.) [21].

Several factors contribute to the composition and transmission of seed microbiomes. Plant genotype, environmental factors, and developmental stages influence seed microbiome composition [18]. Selection is the key ecological process driving dominant taxa succession during seed filling and maturation [20]. Storage conditions can affect seed microbiota conservation, with initial seed drying before storage reducing microbial composition [7].

Seed microbiome assembly and transmission involve complex processes. Abundance-based models classify microbes, with many late colonizers dominating at ripening. Temporal patterns are shaped by niche changes and neutrality [18]. The transition from seed to seedling involves significant changes in microbial population sizes and community structure [20].

Understanding seed microbiomes is crucial as seed-associated microbes support germination, protect against pathogens, and enhance seedling nutrition and vigor [21]. The seed microbiome links the maternal and offspring environments, influencing plant ecology and evolution [7]. Manipulating seed microbiomes offers potential for improving crop establishment and developing microbial-based solutions for agriculture [4,7,20].

In other words, recent research has revealed the complexity of seed microbiome composition and transmission, highlighting its importance in plant health and agricultural practices. Further studies are needed to fully elucidate the mechanisms of microbial inheritance (the transmission of microbes from parent plants to their offspring) and their implications for sustainable agriculture.

3. Beneficial Effects of Seed-Associated Microbes

Seed microbes are vital for plant health, growth, and productivity. Recent research has revealed several key benefits of these microorganisms. Seed-associated microbes significantly improve germination rates and seedling vigor. Beneficial microbes boost germination, seedling vigor, biomass, and help overcome seed-related stresses during and after emergence [6,8,22,23].

Beneficial microbes initiate complex biochemical interactions during seed germination, priming metabolic pathways to enhance vigor and uniformity. Cyanobacteria such as *Spirulina platensis* enhance photosynthetic capacity in emerging seedlings by upregulating chlorophyll synthesis genes, particularly under cadmium stress [8]. In a study on mung bean seeds, the addition of cultured microbes from domestic soil significantly enhanced germination frequency compared to controls [24].

Seed microbes enhance plant growth, with PGPB boosting crop yields by 12–20% (Figure 1) [9]. Seed endophytic bacteria enhance crop growth and yields in plants like rice, maize, wheat, and tomatoes [25]. Microbes produce phytohormones like IAA, gibberellins, and cytokinin, boosting root growth, biomass, and plant development [25]. For example, *Bacillus subtilis* and *Pseudomonas fluorescens* secrete hydrolytic enzymes such as α-amylase and invertase, which mobilize stored carbohydrates in seeds, providing energy for radicle emergence [8,26]. These bacteria produce phytohormones like IAA, promoting cell elongation and lateral root growth in wheat and maize seedlings [9].

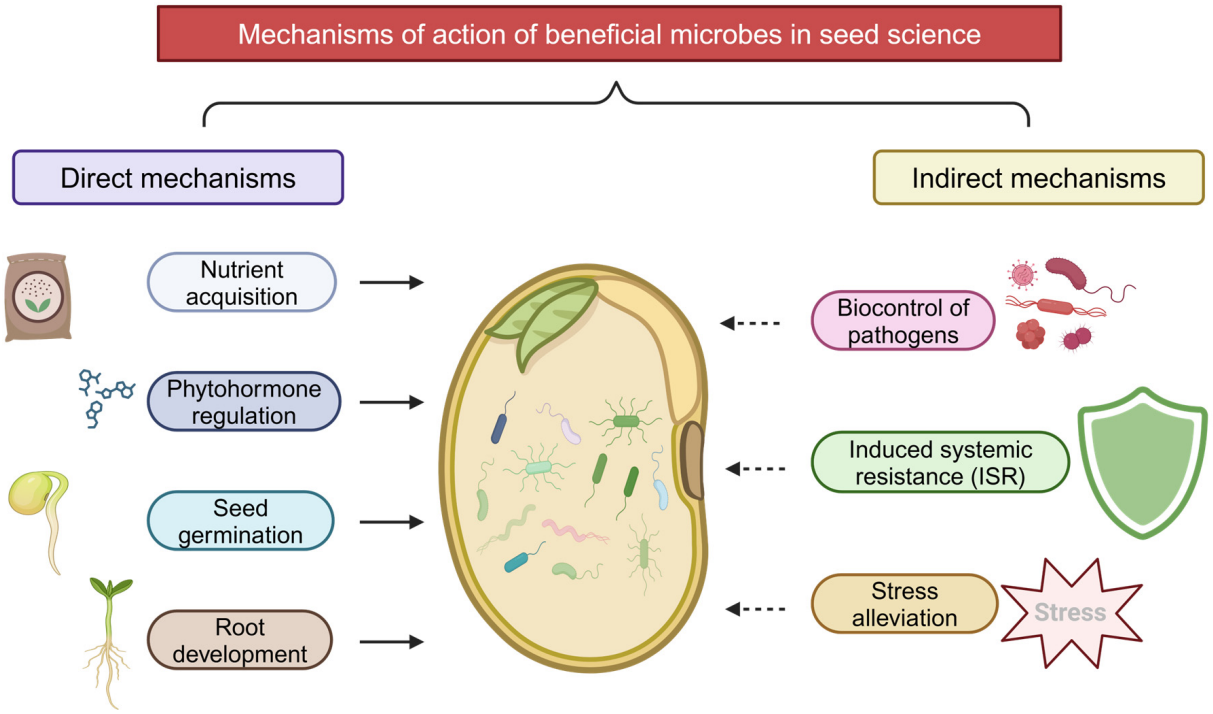


Figure 1. Mechanisms of action of beneficial microbes in seed science. Beneficial microbes play a crucial role in seed science by enhancing plant growth, resilience, and productivity through diverse direct and indirect mechanisms. Their application in agricultural practices, such as seed treatments or microbiome engineering, provides sustainable solutions for improving crop performance under variable environmental conditions. Modified from [10,27]. Created in Biorender. Piao Yang. (2025) (https://BioRender.com/n92c401, accessed on 1 January 2025).

Seed-associated microbes can also improve nutrient uptake and availability. Some microbes, like mycorrhizal fungi, increase the surface area of plant roots and improve nutrient uptake by creating an extensive mycelial network [28]. Certain bacteria can even solubilize phosphorus, potassium, and zinc, making these nutrients more available to plants [9].

Seed microbes enhance plant resilience to environmental stresses like drought and salinity [10,25,29,30]. Seed biopriming with beneficial microorganisms increases plant resilience and effectiveness under adverse conditions [9].

Seed-associated microbes also play a crucial role in protecting plants from different pathogens. Some microbes produce compounds that inhibit the growth of harmful

pathogens in the soil, reducing the risk of disease [6,22,29,30]. Seed biopriming offers eco-friendly biotic stress management, serving as an alternative to chemical fungicides [9,10,22]. The seed microbiome influences plant ecology and evolution by enhancing nutrient uptake, pathogen resilience, and abiotic stress tolerance. It also aids plant establishment, colonization, and spread, offering insights into conservation and invasion ecology [31].

4. Innovative Approaches to Seed Microbiome Engineering

Recent advances in seed microbiome engineering have opened new possibilities for enhancing crop performance and sustainability (Figure 2). Novel approaches for manipulating seed microbiomes include synthetic microbial communities (SynComs), endophytic microbial introduction, host-mediated selection, biopriming, microbiome engineering via environmental factors, and genome-wide association studies to identify genetic loci associated with seed endophyte diversity.

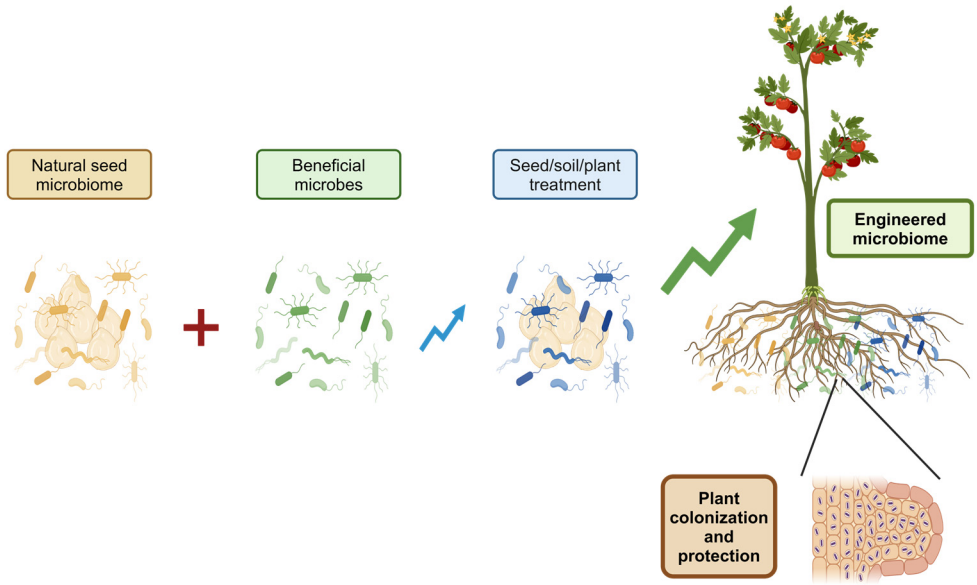


Figure 2. Seed microbiome engineering. Seed microbial communities, shaped by genotype, environment, and management, are vital for sustainable agriculture. Modified from [6,29,32]. Created in Biorender. Piao Yang. (2025) (https://BioRender.com/t57t826, accessed on 1 January 2025).

Researchers are exploring innovative approaches to manipulate seed microbiomes for enhanced crop performance. The development of SynComs shows promise for seedling microbiota engineering. SynComs offer a promising method to engineer plant microbiota. Arnault et al. (2024) showed that seed inoculation with SynComs effectively shaped seedling microbiota, with SynComs comprising 80% of the community. Strain abundance on seeds was identified as a key driver of colonization, with *Enterobacteriaceae* and *Erwiniaceae* as strong colonizers and *Bacillaceae* and *Microbacteriaceae* as weak colonizers [12].

A new framework integrates top-down and bottom-up strategies to engineer natural microbiomes. Using herbicides and degrader inoculation, researchers guided microbiomes toward enhanced bioremediation. They also developed Super Community Combinations (SuperCC), a metabolic modeling tool, to analyze interactions and predict microbiome performance [33].

Recent research has focused on harnessing seed-associated endophytes for improved crop performance. Host genetics play a crucial role in shaping seed microbiome composition. Recent genome-wide association studies (GWASs) have identified plant loci linked to the abundance and diversity of specific microbial taxa within seeds. For example, Tabassum et al. (2024) demonstrated that in fonio millet, distinct genetic regions are associated with

microbial recruitment, suggesting a heritable basis for seed microbiome assembly. These findings underscore the potential to selectively breed or engineer crops with traits that favor beneficial microbial associations, paving the way for genotype-informed microbiome management strategies [34].

Understanding and manipulating microbial inheritance has emerged as a key approach in seed microbiome engineering. Researchers divide inheritance into three stages: plant-to-seed, seed dormancy, and seed-to-seedling [2]. The vertical transmission of seed microbiomes is crucial for forming microbial communities and defending against phytopathogens [1].

Recent studies have explored engineering seed microbiomes for targeted functions. Researchers have investigated the potential of seed microbe engineering for producing targeted metabolites or antimicrobial compounds to improve plant biomass and yield under stress conditions [34]. Studies have focused on introducing beneficial bacteria at flowering to engineer the microbiomes of progeny seeds [1].

These innovative approaches to seed microbiome engineering offer promising avenues for enhancing crop resilience, productivity, and sustainability in agriculture. As research in this field continues to advance, we can expect to see more sophisticated and targeted methods for manipulating seed microbiomes to improve crop performance.

5. Seed Biopriming with Beneficial Microorganisms

Seed biopriming with beneficial microorganisms has emerged as a promising approach for enhancing crop performance and sustainability. This technique merges seed priming with beneficial microbes, boosting plant growth, stress tolerance, and agricultural productivity.

Seed biopriming applies beneficial microbes to seeds with controlled hydration, enabling microbial colonization and metabolic activation without triggering germination [35]. Many microorganisms or beneficial microbes have shown effectiveness in seed biopriming (Table 1). For example, *Bacillus*, *Pseudomonas*, and *Azospirillum*, and *Microbacterium* species in bacteria [35,36]; *Trichoderma* species in fungi [37]; and *Cyanobacteria*, which is particularly useful for dryland restoration [36]. Hanif et al. (2024) highlighted the potential of seed biopriming with beneficial microorganisms to enhance crop resilience and effectiveness under adverse conditions, potentially increasing crop production by 12–20% [38].

Table 1. Selected beneficial microbes in seed science.

Beneficial Microbes	Beneficial Effects	Mode of Action	Example Strains	References
Trichoderma harzianum	Improves seed germination and enhances plant growth; provides stress tolerance against biotic and abiotic factors; alleviates physiological stresses in germinating seeds and seedlings; promotes root colonization and enhances disease resistance.	Stress Tolerance Enhancement; Seed Germination and Seedling Vigor Enhancement	*T. harzianum strain* T22; *T. harzianum strain* S. INAT	[39–42]
Bacillus subtilis	Enhances seed germination rates and promotes plant growth; improves stress tolerance by increasing chlorophyll content and root length under saline conditions; acts as a biocontrol agent against pathogens; stimulates plant growth through production of phytohormones and stress-related metabolites.	Seed Germination and Seedling Vigor Enhancement; Disease Suppression;	*B. subtilis* HS5B5; *B. subtilis* ER-08; *B. subtilis* QM3	[43–46]

Table 1. *Cont.*

Beneficial Microbes	Beneficial Effects	Mode of Action	Example Strains	References
Pseudomonas fluorescens	Enhances seed germination and promotes plant growth by producing phytohormones; improves nutrient acquisition; suppresses various plant diseases through production of antimicrobial compounds.	Seed Germination and Seedling Vigor Enhancement; Direct Growth Promotion	*P. fluorescens* SP007S; *P. fluorescens* F113	[47–50]
Paenibacillus polymyxa	Promotes plant growth and enhances stress tolerance; suppresses diseases by producing various antibiotics; improves germination and protects plants against pathogenic fungi, oomycetes, and bacteria.	Direct Growth Promotion; Disease Suppression	*P. polymyxa* HK4; *Paenibacillus polymyxa* E681	[51–53]
Variovorax sp.	Enhances wheat germination under salt stress conditions; improves biomass; reduces lipid peroxidation.	Direct Growth Promotion; Stress Tolerance Enhancement; Seed Germination and Seedling Vigor Enhancement	*Variovorax* sp. P1R9; *Variovorax* sp. EBFNA2	[54,55]
Azospirillum brasilense	Enhances seed germination; increases root length; promotes plant growth through auxin production, stimulating root development and improving nutrient uptake; enhances stress tolerance in plants.	Direct Growth Promotion; Seed Germination and Seedling Vigor Enhancement	*Azospirillum brasilense* Ab-V5; *Azospirillum brasilense* Ab-V6; *Azospirillum brasilense* Sp245	[56,57]

Biopriming significantly improves seed germination rates, uniformity, and seedling vigor [9]. Studies have reported increases in germination potential by up to 60% compared to control groups [58]. Biopriming with PGPB can boost crop yields by 12–20% [9]. This improvement is attributed to enhanced nutrient uptake, hormone production, and overall plant fitness [35,36]. Bioprimed seeds show increased resilience to both biotic and abiotic stresses, including improved tolerance to drought, salinity, and heavy metals [36,58] and enhanced resistance against soil-borne pathogens [35,36]. Seed biopriming offers an environmentally friendly alternative to chemical fungicides and fertilizers, aligning with sustainable agriculture goals [9].

Recent research has demonstrated the effectiveness of biopriming across a diverse range of crops, highlighting its potential to enhance agricultural productivity and resilience. In wheat, biopriming has been shown to improve drought tolerance and boost germination potential [58]. Carrot seeds treated with biopriming techniques have exhibited enhanced germination rates and overall plant growth promotion [9]. Furthermore, the benefits of biopriming extend to other major crops such as maize, barley, pea, tomato, and sunflower, where significant improvements have been observed in germination rates, seed viability, and ultimately, crop yield [36]. These findings collectively underscore the versatility and efficacy of biopriming as a promising approach in modern agriculture, offering potential solutions to various challenges faced by farmers across different crop types. Microbial efficacy depends on strain–plant compatibility. For example, *Trichoderma virens* isolates exhibit 40% variability in soybean germination outcomes, necessitating tailored formulations [8]. Advances in nanoencapsulation (e.g., chitosan-coated *Pseudomonas* spp.) prolong viability during storage, maintaining 90% cell viability after 12 months [59]. Research is needed

on thermotolerant strains (e.g., *Geobacillus* spp.) for seed treatments in warming climates. Preliminary trials show *Geobacillus stearothermophilus* enhances rice germination at 42 °C, though field validation is pending [9].

In conclusion, seed biopriming with beneficial microorganisms represents a significant advancement in sustainable agriculture, offering a multifaceted approach to improving crop performance and resilience. As research in this field continues to evolve, it holds exciting potential for addressing global food security challenges while promoting environmentally friendly farming practices.

6. Specific Microbial Strains and Their Effects

Recent studies show specific microbial strains significantly impact seed germination, plant growth, and stress tolerance (Table 1). *T. harzianum* demonstrated the greatest inhibition of seed fungal communities like *Alternaria* sp. and *Fusarium* spp. in cucumber seeds. It significantly improved seed germination (88.75%), shoot length (14.58 cm), root length (13.58 cm), and seedling vigor (2501.31) [39]. *T. viride* and *T. virens* also showed strong inhibition of seed fungal communities and improvements in seed germination and seedling growth, though slightly less than *T. harzianum* [39]. Applying T. viride with Pseudomonas fluorescens to cabbage seeds improved seedling vigor, root length, biomass, and chlorophyll content [60].

For example, *Bacillus subtilis* has been shown to solubilize potassium and phosphorus and produce indole acetic acid (IAA), which contribute to improved seed germination and plant growth [9]. However, under specific test conditions involving cucumber seeds infected with seed-borne fungi such as *Fusarium* spp. and *Alternaria* spp., *Trichoderma harzianum* demonstrated superior efficacy in improving seedling vigor and pathogen suppression [39]. The enhanced effectiveness of Trichoderma species is likely due to their production of cell wall–degrading enzymes (e.g., chitinases, glucanases), competition for nutrients and space, and ability to induce systemic resistance in host plants. Both *Trichoderma* and *Bacillus* strains promote growth through phytohormone production, nutrient solubilization, and modulation of plant defense signaling pathways. For instance, *B. subtilis* can stimulate ethylene and jasmonate pathways, enhancing plant tolerance to environmental stress, while *T. harzianum* boosts phenolic content and peroxidase activity, strengthening physical barriers against pathogen invasion [6,23,61–63].

Pseudomonas fluorescens effectively controls soft rot caused by *Pectobacterium carotovorum* in kale [64]. When applied in combination with *T. viride* to cabbage seeds, *P. fluorescens* significantly improved seedling quality characteristics and yield-related traits [60].

Mycorrhizal fungi (*Rhizophagus irregularis*) and *Trichoderma* spp. modulate root exudation patterns, releasing metabolites that attract symbiotic microbes while suppressing pathogens. In wheat, *Trichoderma harzianum* increases phenolic compounds and peroxidase activity, reinforcing cell walls against oxidative stress. Similarly, *Azospirillum lipoferum* enhances nitrogen fixation in maize, improving radicle growth and early biomass accumulation [8] (Table 1).

These findings demonstrate the diverse and significant effects of specific microbial strains on plant health and productivity. The research emphasizes the potential of these microorganisms in sustainable agriculture practices, particularly in enhancing crop resilience to biotic and abiotic stresses.

7. Mechanisms of Action

Recent research has revealed several key mechanisms through which beneficial seed-associated microbes promote plant growth and enhance stress tolerance. These mechanisms

can be broadly categorized into direct growth promotion, stress tolerance enhancement, and disease suppression (Figure 1).

7.1. Direct Growth Promotion

Beneficial microbes promote plant growth by producing hormones like IAA, gibberellins, and cytokinins, which enhance root elongation, biomass, and development [8]. Many beneficial bacteria can solubilize essential nutrients like phosphorus, potassium, and zinc, making them more readily available for plant uptake [65]. Certain bacteria, especially rhizobia in legumes, can fix atmospheric nitrogen, reducing the need for synthetic fertilizers [9]. For instance, *Bacillus gaemokensis* upregulates salicylic acid (SA), ethylene (ET), and jasmonic acid (JA)pathways in cucumbers, conferring systemic resistance against bacterial pathogens and insect herbivores [66]. Cyclodipeptides from *Bacillus* strains activate defense-related genes, such as *PR-1* and *PDF1.2*, even before pathogen exposure [66]. In rice, biopriming with *Paenibacillus yonginensis* alters DNA methylation patterns, enhancing drought tolerance through sustained expression of osmoprotectant genes [9,36].

7.2. Stress Tolerance Enhancement

Beneficial microbes boost drought tolerance by releasing osmolytes, improving seed germination and growth under water stress [65]. Microbes like *Trichoderma harzianum* improve the activities of antioxidant enzymes (SOD, APX, CAT, POD) in plants, enhancing their ability to cope with oxidative stress [8]. For example, in sunflower, *Paraburkholderia phytofirmans* upregulates superoxide dismutase (SOD) and catalase (CAT), lowering lipid peroxidation by 45% under 150 mM NaCl stress [26,36]. Some bacteria produce 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase, which helps regulate ethylene levels in plants, improving stress tolerance [65]. Microbial consortia mitigate drought through osmolyte synthesis. *Bacillus subtilis* QST 713 increases proline levels in wheat seedlings, maintaining cell turgor and reducing electrolyte leakage by 30% [9]. Research focuses on developing microbial inoculants to boost crop resilience to climate change by improving seed germination and seedling growth under stresses like drought, salinity, and extreme temperatures [59]. The potential of seed-associated microbes in promoting sustainable agriculture and ecosystem restoration is gaining attention.

7.3. Disease Suppression

Beneficial microbes protect plants by producing antibiotics that suppress pathogens [6,10,13]. Certain microbes activate plant defenses, enhancing resistance to various pathogens [6,23,30,67]. Beneficial microbes can outcompete pathogens for nutrients and space in the rhizosphere [9,10]. Seed treatments with *Bacillus velezensis* CMRP 4490 produce lipopeptides (e.g., surfactin) that disrupt Fusarium graminearum hyphae, cutting infection rates by 70% in soybean [8]. *Trichoderma harzianum* induces systemic resistance in tomatoes via β-1,3-glucanase and chitinase expression, reducing *Botrytis cinerea* incidence by 60% [8,26].

Beneficial microbes directly influence seed germination and seedling development. Microbes can increase the activity of germination-related enzymes like α-amylase and invertase, improving seed germination and seedling vigor [8,29]. Microbes also help mobilize seed reserves, providing energy for seedling growth [8]. In addition to promoting plant growth and stress tolerance, certain microbes contribute to phytoremediation by enhancing a plant's ability to tolerate and accumulate heavy metals. These microbes can sequester toxic elements, reduce metal mobility, or stimulate the production of metal-chelating compounds. Their activities facilitate root development and biomass accumulation even in contaminated soils, making them valuable for environmental cleanup and sustainable agriculture [68,69]. For example, *Enterobacter* spp. in sunflower have been shown to enhance phytochelatin synthesis, allowing plants to chelate and compartmentalize toxic metals such

as lead and arsenic in root vacuoles [36,59]. Similarly, Spirulina platensis coatings can restrict cadmium translocation in maize through extracellular sequestration and activation of glutathione-S-transferase, reducing shoot cadmium accumulation by 57% [8]. *Spirulina platensis* coatings restrict cadmium translocation in maize, reducing shoot Cd accumulation by 57% through extracellular sequestration and glutathione-S-transferase activation [8]. Similarly, *Enterobacter* spp. in sunflower enhance phytochelatin synthesis, chelating lead and arsenic in root vacuoles [36,59].

These mechanisms demonstrate the multifaceted ways in which beneficial seed-associated microbes contribute to plant health and productivity. The complexity and diversity of these interactions highlight the potential for developing targeted microbial treatments to address specific agricultural challenges, from improving crop yields to enhancing resilience against climate change-induced stresses [15,65].

8. Conclusions and Future Directions

Recent advances in beneficial microbes for seed science have revealed promising avenues for enhancing crop performance, stress resilience, and sustainability. Seed-associated microbes play vital roles in germination, seedling establishment, and long-term plant health, with evidence supporting their vertical transmission from parent plants to offspring—suggesting a heritable route for improving crop traits across generations. Applications such as seed biopriming have demonstrated significant potential in boosting germination rates, seedling vigor, and productivity. As interest grows in microbial inheritance and transmission, researchers are exploring strategies like introducing beneficial microbes during flowering to engineer the microbiomes of progeny seeds. These developments open exciting new directions for integrating microbiome-based tools into modern agriculture and ecosystem restoration [38].

Despite growing interest and encouraging findings, several limitations constrain the full implementation of seed microbiome engineering in agriculture. A major challenge lies in the inconsistent performance of microbial inoculants across different environmental conditions and crop systems. Microbial survival, colonization efficiency, and interactions with native microbiota remain difficult to predict. Moreover, a limited understanding of microbe–microbe and host–microbe interactions at the systems level hampers the rational design of synthetic communities. Regulatory frameworks for microbial products vary widely and may delay commercialization. Finally, most studies are confined to model or major crops, underscoring the need for broader field validation across diverse agroecosystems [38,70].

Future research aims to engineer seed microbiomes to produce targeted metabolites or antimicrobials, boosting plant biomass and yield under stress [34]. The application of advanced -omics technologies is providing deeper insights into seed–microbe interactions. Improving the formulation and delivery of beneficial microbes for seed applications is crucial. Research is needed to develop more effective seed coating technologies that ensure the viability and efficacy of beneficial microbes during storage and after planting [59].

Author Contributions: Conceptualization, supervision, writing—original draft preparation, writing—review and editing, and visualization: P.Y.; writing—review and editing: L.L., A.C., G.A.M., S.S., S.X., Y.X. and S.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable.

Data Availability Statement: Available from the corresponding author upon a reasonable request.

Acknowledgments: We acknowledge Huang Lab's members for the fruitful discussion on this topic.

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

References

1. Sun, Z.; Adeleke, B.S.; Shi, Y.; Li, C. The Seed Microbiomes of Staple Food Crops. *Microb. Biotechnol.* **2023**, *16*, 2236–2249. [CrossRef] [PubMed]
2. Abdelfattah, A.; Tack, A.J.M.; Lobato, C.; Wassermann, B.; Berg, G. From Seed to Seed: The Role of Microbial Inheritance in the Assembly of the Plant Microbiome. *Trends Microbiol.* **2023**, *31*, 346–355. [CrossRef] [PubMed]
3. Hone, H.; Mann, R.; Yang, G.; Kaur, J.; Tannenbaum, I.; Li, T.; Spangenberg, G.; Sawbridge, T. Profiling, Isolation and Characterisation of Beneficial Microbes from the Seed Microbiomes of Drought Tolerant Wheat. *Sci. Rep.* **2021**, *11*, 11916. [CrossRef]
4. Yang, P.; Condrich, A.; Lu, L.; Scranton, S.; Hebner, C.; Sheykhhasan, M.; Ali, M.A. Genetic Engineering in Bacteria, Fungi, and Oomycetes, Taking Advantage of CRISPR. *DNA* **2024**, *4*, 427–454. [CrossRef]
5. Zhang, D.; Xu, F.; Wang, F.; Le, L.; Pu, L. Synthetic Biology and Artificial Intelligence in Crop Improvement. *Plant Commun.* **2025**, *6*, 101220. [CrossRef]
6. Yang, P.; Yuan, P.; Liu, W.; Zhao, Z.; Bernier, M.C.; Zhang, C.; Adhikari, A.; Opiyo, S.O.; Zhao, L.; Banks, F.; et al. Plant Growth Promotion and Plant Disease Suppression Induced by *Bacillus amyloliquefaciens* Strain GD4a. *Plants* **2024**, *13*, 672. [CrossRef]
7. Jonkers, W.; Gundel, P.E.; Verma, S.K.; White, J.F. Editorial: Seed Microbiome Research. *Front. Microbiol.* **2022**, *13*, 943329. [CrossRef]
8. Cardarelli, M.; Woo, S.L.; Rouphael, Y.; Colla, G. Seed Treatments with Microorganisms Can Have a Biostimulant Effect by Influencing Germination and Seedling Growth of Crops. *Plants* **2022**, *11*, 259. [CrossRef]
9. Fiodor, A.; Ajijah, N.; Dziewit, L.; Pranaw, K. Biopriming of Seed with Plant Growth-Promoting Bacteria for Improved Germination and Seedling Growth. *Front. Microbiol.* **2023**, *14*, 1142966. [CrossRef]
10. Yang, P.; Condrich, A.; Scranton, S.; Hebner, C.; Lu, L.; Ali, M.A. Utilizing Plant Growth-Promoting Rhizobacteria (PGPR) to Advance Sustainable Agriculture. *Bacteria* **2024**, *3*, 434–451. [CrossRef]
11. Mitter, B.; Pfaffenbichler, N.; Flavell, R.; Compant, S.; Antonielli, L.; Petric, A.; Berninger, T.; Naveed, M.; Sheibani-Tezerji, R.; von Maltzahn, G.; et al. A New Approach to Modify Plant Microbiomes and Traits by Introducing Beneficial Bacteria at Flowering into Progeny Seeds. *Front. Microbiol.* **2017**, *8*, 11. [CrossRef]
12. Arnault, G.; Marais, C.; Préveaux, A.; Briand, M.; Poisson, A.-S.; Sarniguet, A.; Barret, M.; Simonin, M. Seedling Microbiota Engineering Using Bacterial Synthetic Community Inoculation on Seeds. *FEMS Microbiol. Ecol.* **2024**, *100*, fiae027. [CrossRef] [PubMed]
13. Rocha, I.; Ma, Y.; Souza-Alonso, P.; Vosátka, M.; Freitas, H.; Oliveira, R.S. Seed Coating: A Tool for Delivering Beneficial Microbes to Agricultural Crops. *Front. Plant Sci.* **2019**, *10*, 1357. [CrossRef] [PubMed]
14. Meza, C.; Valenzuela, F.; Echeverría-Vega, A.; Gomez, A.; Sarkar, S.; Cabeza, R.A.; Arencibia, A.D.; Quiroz, K.; Carrasco, B.; Banerjee, A. Plant-Growth-Promoting Bacteria from Rhizosphere of Chilean Common Bean Ecotype (*Phaseolus vulgaris* L.) Supporting Seed Germination and Growth against Salinity Stress. *Front. Plant Sci.* **2022**, *13*, 1052263. [CrossRef]
15. Efthimiadou, A.; Katsenios, N.; Chanioti, S.; Giannoglou, M.; Djordjevic, N.; Katsaros, G. Effect of Foliar and Soil Application of Plant Growth Promoting Bacteria on Growth, Physiology, Yield and Seed Quality of Maize under Mediterranean Conditions. *Sci. Rep.* **2020**, *10*, 21060. [CrossRef] [PubMed]
16. Fadiji, A.E.; Xiong, C.; Egidi, E.; Singh, B.K. Formulation Challenges Associated with Microbial Biofertilizers in Sustainable Agriculture and Paths Forward. *J. Sustain. Agric. Environ.* **2024**, *3*, e70006. [CrossRef]
17. Díaz-Rodríguez, A.M.; Parra Cota, F.I.; Cira Chávez, L.A.; García Ortega, L.F.; Estrada Alvarado, M.I.; Santoyo, G.; de los Santos-Villalobos, S. Microbial Inoculants in Sustainable Agriculture: Advancements, Challenges, and Future Directions. *Plants* **2025**, *14*, 191. [CrossRef]
18. Kim, H.; Jeon, J.; Lee, K.K.; Lee, Y.-H. Longitudinal Transmission of Bacterial and Fungal Communities from Seed to Seed in Rice. *Commun. Biol.* **2022**, *5*, 1–14. [CrossRef]
19. Simonin, M.; Briand, M.; Chesneau, G.; Rochefort, A.; Marais, C.; Sarniguet, A.; Barret, M. Seed Microbiota Revealed by a Large-Scale Meta-Analysis Including 50 Plant Species. *New Phytol.* **2022**, *234*, 1448–1463. [CrossRef]
20. Chesneau, G.; Laroche, B.; Préveaux, A.; Marais, C.; Briand, M.; Marolleau, B.; Simonin, M.; Barret, M. Single Seed Microbiota: Assembly and Transmission from Parent Plant to Seedling. *mBio* **2022**, *13*, e01648-22. [CrossRef]
21. Johnston-Monje, D.; Gutiérrez, J.P.; Lopez-Lavalle, L.A.B. Seed-Transmitted Bacteria and Fungi Dominate Juvenile Plant Microbiomes. *Front. Microbiol.* **2021**, *12*, 737616. [CrossRef]
22. Yang, P. *Exploring Plant-Microbe Interactions Through the Lens of Beneficial Bacteria*; The Ohio State University: Columbus, OH, USA, 2023.
23. Yang, P.; Bokros, N.; Debolt, S.; Zhao, Z.; Xia, Y. Genome Sequence Source of *Bacillus amyloliquefaciens* Strain GD4a, a Bacterial Endophyte Associated with Switchgrass Plants. *Phytobiomes J.* **2022**, *6*, 354–357. [CrossRef]
24. Singam, R.; Azhari, A.; Patmanathan, S.N. Microbes Cultured from Garden Soil Positively Impact Seed Germination and Plant Growth. *J. Emerg. Investig.* **2021**. [CrossRef] [PubMed]
25. L'Hoir, M.; Duponnois, R. Combining the Seed Endophytic Bacteria and the Back to the Future Approaches for Plant Holonbiont Breeding. *Front. Agron.* **2021**, *3*, 724450. [CrossRef]

26. Srivastava, S.; Tyagi, R.; Sharma, S. Seed Biopriming as a Promising Approach for Stress Tolerance and Enhancement of Crop Productivity: A Review. *J. Sci. Food Agric.* **2024**, *104*, 1244–1257. [CrossRef] [PubMed]
27. Santoyo, G.; Kumar, A.; Babalola, O.O. The Role of Microbial Seed Endophytes in Agriculture: Mechanisms and Applications. *Cereal Res. Commun.* **2024**, *53*, 43–55. [CrossRef]
28. Wahab, A.; Muhammad, M.; Munir, A.; Abdi, G.; Zaman, W.; Ayaz, A.; Khizar, C.; Reddy, S.P.P. Role of Arbuscular Mycorrhizal Fungi in Regulating Growth, Enhancing Productivity, and Potentially Influencing Ecosystems under Abiotic and Biotic Stresses. *Plants* **2023**, *12*, 3102. [CrossRef]
29. Yang, P.; Liu, W.; Yuan, P.; Zhao, Z.; Zhang, C.; Opiyo, S.O.; Adhikari, A.; Zhao, L.; Harsh, G.; Xia, Y. Plant Growth Promotion and Stress Tolerance Enhancement through Inoculation with *Bacillus proteolyticus* OSUB18. *Biology* **2023**, *12*, 1495. [CrossRef]
30. Yang, P.; Zhao, Z.; Fan, J.; Liang, Y.; Bernier, M.C.; Gao, Y.; Zhao, L.; Opiyo, S.O.; Xia, Y. *Bacillus proteolyticus* OSUB18 Triggers Induced Systemic Resistance against Bacterial and Fungal Pathogens in Arabidopsis. *Front. Plant Sci.* **2023**, *14*, 1078100. [CrossRef]
31. War, A.F.; Bashir, I.; Reshi, Z.A.; Kardol, P.; Rashid, I. Insights into the Seed Microbiome and Its Ecological Significance in Plant Life. *Microbiol. Res.* **2023**, *269*, 127318. [CrossRef]
32. Compant, S.; Cassan, F.; Kostić, T.; Johnson, L.; Brader, G.; Trognitz, F.; Sessitsch, A. Harnessing the Plant Microbiome for Sustainable Crop Production. *Nat. Rev. Microbiol.* **2025**, *23*, 9–23. [CrossRef] [PubMed]
33. Ruan, Z.; Chen, K.; Cao, W.; Meng, L.; Yang, B.; Xu, M.; Xing, Y.; Li, P.; Freilich, S.; Chen, C.; et al. Engineering Natural Microbiomes toward Enhanced Bioremediation by Microbiome Modeling. *Nat. Commun.* **2024**, *15*, 4694. [CrossRef] [PubMed]
34. Tabassum, N.; Ahmed, H.I.; Parween, S.; Sheikh, A.H.; Saad, M.M.; Krattinger, S.G.; Hirt, H. Host Genotype, Soil Composition, and Geo-Climatic Factors Shape the Fonio Seed Microbiome. *Microbiome* **2024**, *12*, 11. [CrossRef]
35. Mahmood, A.; Turgay, O.C.; Farooq, M.; Hayat, R. Seed Biopriming with Plant Growth Promoting Rhizobacteria: A Review. *FEMS Microbiol. Ecol.* **2016**, *92*, fiw112. [CrossRef] [PubMed]
36. Singh, P.; Vaishnav, A.; Liu, H.; Xiong, C.; Singh, H.B.; Singh, B.K. Seed Biopriming for Sustainable Agriculture and Ecosystem Restoration. *Microb. Biotechnol.* **2023**, *16*, 2212–2222. [CrossRef]
37. Swain, H.; Adak, T.; Mukherjee, A.K.; Sarangi, S.; Samal, P.; Khandual, A.; Jena, R.; Bhattacharyya, P.; Naik, S.K.; Mehetre, S.T.; et al. Seed Biopriming with Trichoderma Strains Isolated from Tree Bark Improves Plant Growth, Antioxidative Defense System in Rice and Enhance Straw Degradation Capacity. *Front. Microbiol.* **2021**, *12*, 633881. [CrossRef]
38. Hanif, M.S.; Tayyab, M.; Baillo, E.H.; Islam, M.M.; Islam, W.; Li, X. Plant Microbiome Technology for Sustainable Agriculture. *Front. Microbiol.* **2024**, *15*, 1500260. [CrossRef]
39. Sharma, A.; Shukla, A.; Gupta, M. Effect of Bioagents on Cucumber Seed Mycoflora, Seed Germination, and Seedling Vigour. *Sci. Rep.* **2023**, *13*, 6052. [CrossRef]
40. Mastouri, F.; Björkman, T.; Harman, G.E. Seed Treatment with *Trichoderma harzianum* Alleviates Biotic, Abiotic, and Physiological Stresses in Germinating Seeds and Seedlings. *Phytopathology* **2010**, *100*, 1213–1221. [CrossRef]
41. Mahmoodian, S.; Kowsari, M.; Motallebi, M.; Zamani, M.; Jahromi, Z.M. Effect of Improved *Trichoderma harzianum* on Growth and Resistance Promotion in Bean Plant. *Braz. Arch. Biol. Technol.* **2022**, *65*, e22210671. [CrossRef]
42. Kthiri, Z.; Jabeur, M.B.; Machraoui, M.; Gargouri, S.; Hiba, K.; Hamada, W. Coating Seeds with *Trichoderma* Strains Promotes Plant Growth and Enhance the Systemic Resistance against Fusarium Crown Rot in Durum Wheat. *Egypt. J. Biol. Pest Control* **2020**, *30*, 139. [CrossRef]
43. Hashem, A.; Tabassum, B.; Fathi Abd_Allah, E. Bacillus Subtilis: A Plant-Growth Promoting Rhizobacterium That Also Impacts Biotic Stress. *Saudi J. Biol. Sci.* **2019**, *26*, 1291–1297. [CrossRef]
44. Song, P.; Zhao, B.; Sun, X.; Li, L.; Wang, Z.; Ma, C.; Zhang, J. Effects of Bacillus Subtilis HS5B5 on Maize Seed Germination and Seedling Growth under NaCl Stress Conditions. *Agronomy* **2023**, *13*, 1874. [CrossRef]
45. Hu, Q.; Liu, R.; Liu, J. Effects of *Bacillus subtilis* QM3 on Germination and Antioxidant Enzymes Activities of Wheat Seeds under Salt Stress. *Open Access Libr. J.* **2019**, *6*, 1–9. [CrossRef]
46. Patel, M.; Islam, S.; Husain, F.M.; Yadav, V.K.; Park, H.-K.; Yadav, K.K.; Bagatharia, S.; Joshi, M.; Jeon, B.-H.; Patel, A. *Bacillus subtilis* ER-08, a Multifunctional Plant Growth-Promoting Rhizobacterium, Promotes the Growth of Fenugreek (*Trigonella Foenum-graecum* L.) Plants under Salt and Drought Stress. *Front. Microbiol.* **2023**, *14*, 1208743. [CrossRef]
47. Mehmood, N.; Saeed, M.; Zafarullah, S.; Hyder, S.; Rizvi, Z.F.; Gondal, A.S.; Jamil, N.; Iqbal, R.; Ali, B.; Ercisli, S.; et al. Multifaceted Impacts of Plant-Beneficial *Pseudomonas* Spp. in Managing Various Plant Diseases and Crop Yield Improvement. *ACS Omega* **2023**, *8*, 22296–22315. [CrossRef] [PubMed]
48. Nilmat, A.; Thepbandit, W.; Chuaboon, W.; Athinuwat, D. *Pseudomonas fluorescens* SP007S Formulations in Controlling Soft Rot Disease and Promoting Growth in Kale. *Agronomy* **2023**, *13*, 1856. [CrossRef]
49. Rivera-Conde, M.I.; Aranda-Ocampo, S.; Carrillo-Castañeda, G.; Gijón-Hernández, A.R.; Bueno-Aguilar, G.M.; Rivera-Conde, M.I.; Aranda-Ocampo, S.; Carrillo-Castañeda, G.; Gijón-Hernández, A.R.; Bueno-Aguilar, G.M. Effect of Fluorescent Pseudomonas on Tomato Seed Germination and Seedling Vigor. *Rev. Chapingo Ser. Hortic.* **2018**, *24*, 121–131. [CrossRef]

50. Lally, R.D.; Galbally, P.; Moreira, A.S.; Spink, J.; Ryan, D.; Germaine, K.J.; Dowling, D.N. Application of Endophytic *Pseudomonas fluorescens* and a Bacterial Consortium to *Brassica napus* Can Increase Plant Height and Biomass under Greenhouse and Field Conditions. *Front. Plant Sci.* **2017**, *8*, 2193. [CrossRef]
51. Langendries, S.; Goormachtig, S. *Paenibacillus polymyxa*, a Jack of All Trades. *Environ. Microbiol.* **2021**, *23*, 5659–5669. [CrossRef]
52. Soni, R.; Rawal, K.; Keharia, H. Genomics Assisted Functional Characterization of *Paenibacillus polymyxa* HK4 as a Biocontrol and Plant Growth Promoting Bacterium. *Microbiol. Res.* **2021**, *248*, 126734. [CrossRef]
53. Jeong, H.; Choi, S.-K.; Ryu, C.-M.; Park, S.-H. Chronicle of a Soil Bacterium: Paenibacillus Polymyxa E681 as a Tiny Guardian of Plant and Human Health. *Front. Microbiol.* **2019**, *10*, 467. [CrossRef]
54. Acuña, J.J.; Rilling, J.I.; Inostroza, N.G.; Zhang, Q.; Wick, L.Y.; Sessitsch, A.; Jorquera, M.A. *Variovorax* Sp. Strain P1R9 Applied Individually or as Part of Bacterial Consortia Enhances Wheat Germination under Salt Stress Conditions. *Sci. Rep.* **2024**, *14*, 2070. [CrossRef] [PubMed]
55. Hirsch, A.M.; Humm, E.; Rubbi, L.; Del Vecchio, G.; Ha, S.M.; Pellegrini, M.; Gunsalus, R.P. Complete Genome of *Variovorax* sp. EBFNA2, Isolated from a Surface-Sterilized Fava Bean Nodule. *Microbiol. Resour. Announc.* **2024**, *13*, e00762-24. [CrossRef]
56. José, J.F.B.d.S.; Hernandes, M.A.S.; Lisboa, B.B.; Volpiano, C.G.; Schlindwein, G.; da Trindade, J.K.; Lattuada, D.S.; Beneduzi, A.; Vargas, L.K. Seed Size and *Azospirillum brasilense* Ab-V5 and Ab-V6 Inoculation Influences Germination and Early Seedling Vigor of *Acacia mearnsii*. *Ciênc. Florest.* **2024**, *34*, e85546. [CrossRef]
57. Méndez-Gómez, M.; Castro-Mercado, E.; López-Bucio, J.; García-Pineda, E. *Azospirillum brasilense* Sp245 Triggers Cytokinin Signaling in Root Tips and Improves Biomass Accumulation in *Arabidopsis* through Canonical Cytokinin Receptors. *Physiol. Mol. Biol. Plants Int. J. Funct. Plant Biol.* **2021**, *27*, 1639–1649. [CrossRef] [PubMed]
58. Shaffique, S.; Imran, M.; Kang, S.-M.; Khan, M.A.; Asaf, S.; Kim, W.-C.; Lee, I.-J. Seed Bio-Priming of Wheat with a Novel Bacterial Strain to Modulate Drought Stress in Daegu, South Korea. *Front. Plant Sci.* **2023**, *14*, 1118941. [CrossRef]
59. Paravar, A.; Piri, R.; Balouchi, H.; Ma, Y. Microbial Seed Coating: An Attractive Tool for Sustainable Agriculture. *Biotechnol. Rep.* **2023**, *37*, e00781. [CrossRef]
60. Vij, S.; Sharma, N.; Sharma, M.; Mohanta, T.K.; Kaushik, P. Application of *Trichoderma viride* and *Pseudomonas fluorescens* to Cabbage (*Brassica oleracea* L.) Improves Both Its Seedling Quality and Field Performance. *Sustainability* **2022**, *14*, 7583. [CrossRef]
61. Yao, X.; Guo, H.; Zhang, K.; Zhao, M.; Ruan, J.; Chen, J. Trichoderma and Its Role in Biological Control of Plant Fungal and Nematode Disease. *Front. Microbiol.* **2023**, *14*, 1160551. [CrossRef]
62. Blake, C.; Christensen, M.N.; Kovács, Á.T. Molecular Aspects of Plant Growth Promotion and Protection by *Bacillus subtilis*. *Mol. Plant-Microbe Interact.* **2021**, *34*, 15–25. [CrossRef] [PubMed]
63. Zhao, Z.; Bokros, N.; DeBolt, S.; Yang, P.; Xia, Y. Genome Sequence Resource of *Bacillus* sp. RRD69, a Beneficial Bacterial Endophyte Isolated from Switchgrass Plants. *Mol. Plant. Microbe Interact.* **2021**, *34*, 1320–1323. [CrossRef] [PubMed]
64. Dumigan, C.R.; Deyholos, M.K. Soil and Seed Both Influence Bacterial Diversity in the Microbiome of the *Cannabis sativa* Seedling Endosphere. *Front. Plant Sci.* **2024**, *15*, 1326294. [CrossRef]
65. Fanai, A.; Bohia, B.; Lalremruati, F.; Lalhriatpuii, N.; Lalrokimi; Lalmuanpuii, R.; Singh, P.K. Zothanpuia Plant Growth Promoting Bacteria (PGPB)-Induced Plant Adaptations to Stresses: An Updated Review. *PeerJ* **2024**, *12*, e17882. [CrossRef] [PubMed]
66. Song, G.C.; Choi, H.K.; Kim, Y.S.; Choi, J.S.; Ryu, C.-M. Seed Defense Biopriming with Bacterial Cyclodipeptides Triggers Immunity in Cucumber and Pepper. *Sci. Rep.* **2017**, *7*, 14209. [CrossRef]
67. Yang, P.; Zhao, Z.; Virag, A.; Becker, T.; Zhao, L.; Liu, W.; Xia, Y. Botrytis Cinerea In-Vivo Inoculation Assays for Early-, Middle- and Late-Stage Strawberries. *Bio Protoc.* **2023**, *13*, e4859. [CrossRef]
68. Khatoon, Z.; Orozco-Mosqueda, M.d.C.; Santoyo, G. Microbial Contributions to Heavy Metal Phytoremediation in Agricultural Soils: A Review. *Microorganisms* **2024**, *12*, 1945. [CrossRef]
69. Montreemuk, J.; Stewart, T.N.; Prapagdee, B. Bacterial-Assisted Phytoremediation of Heavy Metals: Concepts, Current Knowledge, and Future Directions. *Environ. Technol. Innov.* **2024**, *33*, 103488. [CrossRef]
70. O'Callaghan, M.; Ballard, R.A.; Wright, D. Soil Microbial Inoculants for Sustainable Agriculture: Limitations and Opportunities. *Soil Use Manag.* **2022**, *38*, 1340–1369. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.