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Seed Microbiome Engineering: A Novel Strategy for Disease Management and Crop Improvement

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Seeds are central to agriculture, acting as both carriers of plant genetic material and as ecological niches that host diverse microbial communities. This seed microbiome, composed of bacteria, fungi, actinomycetes and yeasts, is acquired either vertically from parent plants or horizontally from the surrounding environment (Nelson, 2018). Far from being incidental, these microorganisms play vital roles in seed germination, seedling vigour, nutrient acquisition, abiotic stress tolerance, and defense against pathogens. Recent research has emphasized that seeds are not sterile units but dynamic microhabitats where plants and microbes co-evolve, influencing crop health and productivity (Adam *et al.*, 2018).

However, seeds are also major vehicles for plant pathogens that pose serious threats to global food security. Fungal pathogens such as *Fusarium oxysporum* and *Aspergillus flavus*, bacterial invaders like *Clavibacter michiganensis* and *Xanthomonas oryzae*, and viruses such as *Soybean mosaic virus*, *Cowpea mosaic virus* are often seed-borne (Dell'Olmo *et al.*, 2023). These pathogens can remain latent, spreading silently through seed trade and initiating devastating epidemics in the field. Conventional seed treatments, including fungicides, hot water, and certification programs, offer limited and often short-lived protection, while concerns over chemical residues and resistance further restrict their use.

Against this backdrop, seed microbiome engineering has emerged as a promising strategy for sustainable agriculture. By enriching or manipulating seed-associated microbes, it is possible to suppress pathogens, induce systemic resistance and promote growth. Beneficial microbes such as *Trichoderma*, *Bacillus* and *Pseudomonas* not only inhibit pathogens but also enhance nutrient uptake and improve tolerance to stresses like drought and salinity. In medicinal plants, they even influence secondary metabolite production (Santoyo *et al.*, 2024). Advances in omics technologies, synthetic biology and delivery systems have made it possible to identify key microbial players and design targeted consortia for seed applications. Thus, seed microbiome engineering represents an innovative integration of plant pathology, seed science and biotechnology, offering long-term, eco-friendly solutions for disease management and crop improvement.

Seed Microbiome: Composition and Ecological Significance

The seed microbiome is established through both vertical transmission, where microbes are inherited from the parent plant via floral tissues and developing embryos and horizontal transmission, where seeds acquire microbes from the surrounding environment during maturation, harvesting and storage (Nelson, 2018). Bacterial genera such as *Pseudomonas*, *Bacillus*, *Enterobacter*, *Streptomyces* and *Rhizobium* are frequently associated with seeds and are known for their capacity to produce growth-promoting hormones, siderophores, and antimicrobial compounds (Guha and Biswas, 2024). Fungal communities are more diverse, comprising both beneficial groups like *Trichoderma* and mycorrhizal fungi, which enhance plant immunity and nutrient uptake, as well as harmful species such as *Fusarium*, *Alternaria*, and *Aspergillus*, which are responsible for seed rot, seedling blight, and toxin contamination. Yeasts and actinomycetes also form an integral part of the seed microbiome, contributing to nutrient cycling and the synthesis of bioactive metabolites.

The functional role of the seed microbiome extends beyond simple colonization. Beneficial microbes can act as the first line of defense by occupying ecological niches that would otherwise be exploited by pathogens. They produce hormones such as indole-3-acetic acid and gibberellins, which stimulate germination and early growth, and enzymes such as ACC deaminase, which reduce stress-induced ethylene levels and enhance tolerance to salinity and drought. In addition, microbes that fix nitrogen or solubilize phosphate improve the nutrient status of the emerging seedling. Together, these functions highlight the ecological importance of the seed microbiome as a natural biological shield and growth promoter.

Seed-Borne Pathogens and Their Agricultural Impact

Seed-borne pathogens remain one of the most persistent challenges in modern agriculture. Fungal pathogens such as *Fusarium oxysporum*, *Alternaria alternata*, and *Aspergillus flavus* are particularly destructive, causing pre- and post-emergence seedling blight and contaminating seeds with toxins that threaten both yield and food safety (Gaur *et al*., 2020). Bacterial pathogens like *Clavibacter michiganensis* and *Xanthomonas* species are transmitted through seeds and act as primary sources of field epidemics, while viral pathogens such as *Cowpea mosaic virus* and *Papaya ringspot virus* exploit seeds to establish systemic infections early in plant development.

The consequences of seed-borne pathogens are not confined to reduced germination or seed viability. They also compromise storage longevity, market quality, and, more importantly, serve as efficient vehicles for spreading diseases across geographical regions through seed trade. Conventional methods of seed health management, including fungicides and physical treatments, are limited in scope and often fail to provide complete eradication of pathogens that reside deep within seed tissues. These shortcomings underline the need for novel strategies, such as microbiome engineering, that can provide more sustainable and long-lasting protection.

Seed Microbiome Engineering: Concepts and Strategies

Seed microbiome engineering refers to the deliberate modification or enrichment of the seed-associated microbial community to favour beneficial functions over harmful ones. One of the most widely studied approaches is microbial inoculation, where seeds are coated, pelleted, or primed with beneficial organisms such as *Trichoderma*, *Bacillus* or *Pseudomonas*. These microbes colonize the seed surface and rhizosphere upon germination, establishing protective and growth-promoting interactions. Another promising strategy is the development of synthetic microbial consortia that combine multiple strains with complementary functions, thereby creating synergistic effects for disease suppression and crop growth.

Advances in biotechnology have expanded the scope of seed microbiome engineering. Genome editing tools like CRISPR/Cas9 can be used to enhance the traits of beneficial microbes, for example by increasing their ability to produce antimicrobial compounds or improving their colonization efficiency. Nanotechnology provides innovative delivery systems that ensure the survival of inoculated microbes during storage and allow their gradual release in the rhizosphere. Furthermore, omics-based approaches such as metagenomics, transcriptomics, and metabolomics enable researchers to analyze microbial diversity and functions in great detail, facilitating the selection of keystone microbes that can play crucial roles in engineered seed microbiomes.

Contribution to Disease Management

One of the most significant benefits of seed microbiome engineering lies in disease management. Beneficial microbes suppress pathogens through direct mechanisms such as competition for nutrients and space, production of antibiotics, and secretion of lytic enzymes like chitinases and glucanases that degrade pathogen cell walls. For instance, *Trichoderma asperellum* applied to maize seeds has been shown to reduce the incidence of *Fusarium* wilt, while *Pseudomonas fluorescens* enhances resistance to bacterial blight in rice (Jia *et al*., 2019). *Bacillus subtilis*, when coated on cotton seeds, effectively prevents damping-off and seedling rot.

In addition to these direct antagonistic effects, seed-associated microbes also stimulate Induced Systemic Resistance (ISR) in plants, priming the immune system to respond more effectively against future attacks. This indirect protection is particularly valuable as it provides broad-spectrum and durable resistance against a range of pathogens. By integrating these mechanisms, seed microbiome engineering creates a multi-layered defense system that reduces reliance on chemical fungicides and ensures healthier crop stands.

Contribution to Crop Improvement

Beyond pathogen suppression, seed microbiome engineering plays a vital role in enhancing overall crop performance. Microbial communities associated with seeds produce phytohormones that accelerate germination, improve seedling vigor, and increase biomass accumulation. They enhance nutrient uptake through biological nitrogen fixation, phosphate solubilization, and siderophore production, which collectively improve soil fertility and crop nutrition (Singh *et al*., 2019). In stress-prone environments, microbes that produce ACC deaminase mitigate the negative effects of ethylene accumulation, enabling plants to withstand salinity, drought, and other abiotic stresses more effectively.

In medicinal and aromatic plants, seed microbiomes exert an additional influence by stimulating the biosynthesis of secondary metabolites. For example, in Kalmegh (*Andrographis paniculata*), endophytic microbes associated with seeds have been reported to enhance the accumulation of andrographolide, a bioactive compound with immense pharmaceutical value (Sharangi *et al*., 2025). Such findings demonstrate the wide-ranging implications of seed microbiome engineering not only for food crops but also for crops with medicinal and industrial importance.

Future Prospects and Challenges

Although the potential of seed microbiome engineering is immense, several challenges must be addressed before it can be widely adopted in agriculture. One major issue is the stability of inoculated microbes during long-term seed storage, as desiccation and adverse storage conditions may reduce microbial viability. Another challenge lies in host–microbe specificity, where beneficial microbes effective in one crop may not exhibit the same results in another due to differences in physiology and ecological compatibility. Regulatory frameworks also need to evolve, as current seed certification standards rarely include microbiome parameters, creating a bottleneck for commercialization.

Nevertheless, the future prospects are encouraging. Advances in synthetic biology can enable the design of tailor-made microbial strains with enhanced functionality, while artificial intelligence and bioinformatics tools can predict optimal microbe–seed combinations for different agro-ecological contexts. Integrating microbiome profiling into seed certification programs could ensure standardized quality and accelerate adoption. Collectively, these innovations have the potential to make microbiome-engineered seeds a cornerstone of sustainable agriculture.

Conclusion

Seed microbiome engineering represents a paradigm shift in agricultural science, uniting the principles of plant pathology, seed technology, and biotechnology into a holistic framework for crop improvement. By transforming seeds into carriers of beneficial microbes, this approach offers sustainable solutions to the dual challenge of disease management and productivity enhancement. It reduces dependence on chemical inputs, strengthens resilience to both biotic and abiotic stresses, and opens new avenues for improving the nutritional and medicinal quality of crops. As global agriculture strives for sustainability, microbiome-engineered seeds are poised to become key drivers of resilient, eco-friendly, and high-yielding farming systems.

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