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Seed Microbiome: The Hidden World That Helps Seeds Survive

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Traditionally, seeds have been considered as self-contained structures made up of an embryo, food reserves and protective tissues. Recent developments in microbiome research have revealed that seeds also contain a variety of bacterial and fungal communities, which are referred to as the seed microbiome. These microorganisms can be found on the surface of seeds as well as inside internal tissues. They are obtained by horizontal acquisition from the environment and vertical transmission from the mother plant. Germination, seedling growth, pathogen control and resistance to environmental stresses like drought are all influenced by the seed microbiome. Seed storage conditions, especially moisture and temperature, also affect its composition. Beneficial seed bacteria can be used for sustainable agriculture through new methods including microbial seed coating, biopriming, and microbiome engineering.

Keywords: Spermosphere, Endophytes, Vertical transmission, Seed vigour, Plant–microbe symbiosis

Introduction

Although a seed may appear to be a dry, dormant structure, it actually contains a hidden colony of bacteria, fungus, and other microbes called the seed microbiome. These microbes can live as endophytes inside seed tissues or on the surface of seeds. Because they can affect germination, seedling vigour, nutrient acquisition, disease resistance and stress tolerance, they are becoming more widely acknowledged as crucial seed companions (Fadiji *et al.*, 2025). The transition from a dry seed to a developing seedling is a critical time for the seed microbiome. The production of phytohormones, enzymes and antimicrobial chemicals by beneficial bacteria may aid in seedling germination and early growth. Additionally, some bacteria can be passed along through seeds from the parent plant to the following generation, giving the growing plant an early microbial community. According to recent studies, bacteria linked with seeds may also assist plants to withstand diseases, salt, drought and temperature stress (Romão *et al.*, 2025). They can increase the availability of nutrients and trigger plant defence systems, strengthening the growing plant's resilience.

Every crop or seed lot has a different seed microbiome composition. Plant genotype, soil, climate, crop management, maternal environment and seed-development circumstances can all have an impact. As a result, comprehending the connection between the seed and its microbes is emerging as a significant new field in seed science. Scientists are currently investigating methods to find and use beneficial seed bacteria using DNA sequencing, metagenomics, microbiome analysis, bio-priming and microbial seed coating. The ultimate objective is to create seeds with a healthy microbial population that promotes successful establishment and survival in addition to good genetic and physiological quality (Xu *et al.*, 2026). Therefore, future climate-resilient and sustainable seed technology may heavily rely on the seed microbiome.

What is the Seed Microbiome?

The varied community of microorganisms connected to a seed, including bacteria, fungus, and other microbes, is referred to as the seed microbiome. These microbes live in many environments both inside and outside of the seed. The area of soil or growing medium immediately around a seed during imbibition is known as the spermosphere and it is here that nutrients and exudates released by the seed affect microbial activity. An epiphytic microbial population is supported by the seed coat (testa) and other external surfaces, whereas endophytic microbes are found in the internal tissues, especially the endosperm and embryo. These endophytes can help in seed germination, seedling growth, nutrient uptake and stress resistance while residing in plant tissues or intercellular gaps without causing stresses (Nelson, 2018; Truyens *et al.*, 2015).

The seed microbiome is typically less diverse but more specialized and selective than the phyllosphere (microbial community on leaves) and rhizosphere (microbial community surrounding roots). A comparatively small number of bacterial and fungal taxa that are frequently detected in various crops and in certain situations, spanning generations, frequently dominate it. Pantoea, Enterobacter, Pseudomonas, and Bacillus are commonly reported bacterial groups, whereas Fusarium is one of the most commonly found fungal genera. These microorganisms have been found in the spermosphere and seeds of a variety of crops, including cereals, legumes, and model plants like Arabidopsis, indicating that some microbial groups are well suited to the seed environment (Matilla, 2025).

Among these, Bacillus and Pseudomonas are especially significant since many of their strains can enhance nutrient availability, stimulate plant development and inhibit pathogenic microbes. Additionally, Pantoea and Enterobacter may aid in the colonization and growth of seeds and seedlings. Seeds may also include fungi including Fusarium, Alternaria, Aspergillus and Cladosporium, though their impact can range from advantageous or neutral to harmful. Therefore, the seed microbiome is a dynamic community of neutral, possibly harmful and beneficial microbes that can affect stress tolerance, disease resistance, seed germination, and seedling growth.

Origins and Assembly of the Seed Microbiome

The seed microbiome is formed through two major processes: vertical transmission from the parent plant and horizontal acquisition from the surrounding environment. Together, these processes determine which microorganisms become associated with the seed and developing seedling.

i. Vertical Transmission

The transfer of microorganisms from the mother plant to its seeds via internal tissues, vascular connections, floral structures or other channels is referred to as vertical transmission. In this manner, the seed and certain microbes are transferred from one generation of plants to the next. Because they may stay connected to the embryo during seed formation, hibernation and subsequent germination, endophytic microbes found inside the embryo are thought to be excellent candidates for true vertical transmission. On the other hand, bacteria that are only found on the seed coat can have been picked up from the surrounding environment either during seed formation or later on during germination. Research has demonstrated that certain core microbial groups can last across multiple generations, indicating that microorganisms associated with seeds may constitute a persistent component of the plant's inherited microbiome (Sánchez-López *et al.*, 2018).

ii. Horizontal Acquisition

When seeds acquire microorganisms from their environment, especially soil, air, water and other plant surfaces, this is known as horizontal acquisition (Shade *et al.*, 2017). During seed imbibition and germination, this process becomes particularly crucial. Sugars, amino acids, and other substances are released into the surrounding spermosphere as the dry seed absorbs water. Microorganisms from the surrounding soil are drawn to these nutrients and quickly colonize the seed surface and developing seedling. The ultimate composition of the seedling microbiome may be influenced by interactions between the newly acquired microbes and the microorganisms already present in the seed (Rezki *et al.*, 2018).

Functional Roles of the Seed Microbiome in Seed Survival

i. Protection Against Pathogens and Decay

Defense is one of the seed microbiome's most direct contributions to survival. In addition to producing antimicrobial chemicals, seed-associated bacteria and fungi can boost the seed's own biochemical defences and compete with pathogens for nutrients and space. For instance, *Abutilon theophrasti* seed-associated microbial assemblages produce a variety of diffusible phenolic chemicals that are believed to help protect seeds from fungal pathogens for extended periods of time in the soil seed bank (Singh *et al.*, 2025).

ii. Regulation of Dormancy and Germination

In addition to protecting seeds from harmful microbes, seed endophytes can control the time of germination by affecting the hormonal balance of the plant. Endogenous seed endophytes have been linked to variations in cytokinin and abscisic acid (ABA) levels in *Lolium rigidum*, which may help sustain and break seed dormancy. Additionally, this interaction might aid the species' successful establishment in environments similar to those seen in the Mediterranean. Seed-associated endophytes have also been shown to improve germination and lower seedling mortality in *Phragmites australis*, suggesting that beneficial microbes might affect the transition of seeds from dormancy to active growth. As a result, seed endophytes may serve as crucial biological regulators of germination, assisting seeds in responding appropriately to environmental cues (Singh *et al.*, 2025).

iii. Enhancing Tolerance to Environmental Stress

Additionally, seeds and young seedlings can benefit greatly from the seed microbiome's ability to withstand abiotic stresses like drought. Seeds can interact with beneficial microbes from the surrounding soil, especially in the spermosphere, when there is a shortage of water. Under drought conditions, these bacteria may assist germination and early seedling growth by producing growth-promoting chemicals, enhancing nutrient availability and controlling plant stress responses. Drought-associated microbial communities have been seen to be comparatively stable in some legume species over the course of subsequent generations, indicating that some stress-adapted microbial interactions may be preserved or passed on with the seed. This opens the possibility of selecting or developing beneficial microbial communities from drought-tolerant plants and using them through bio-priming or microbial seed coating to improve crop establishment and performance under water-limited conditions (Xu *et al.*, 2026).

The Seed Microbiome During Storage and Dormancy

In addition to being crucial for preserving seed viability, seed storage and dormancy have an impact on the survival and composition of the seed microbiome. Microbial activity and seed aging are significantly influenced by the moisture content of the seed. Only bacteria that can withstand desiccation, low temperatures and decreased metabolic activity are likely to survive with the seed during storage and more delicate microbes may progressively disappear. According to studies, extended storage can alter the abundance of specific groups, such as Enterobacteriaceae members and storage-associated fungus and decrease the overall diversity of seed-associated microorganisms (Abdelfattah *et al.*, 2023).

The relationship between seed moisture and microbial activity is particularly important. Greater metabolic and microbiological activity can be supported by higher moisture content, which may hasten seed breakdown and encourage the growth of unwanted microbes. On the other hand, appropriate drying and storage at low temperatures and moisture content lower metabolic activity and prolong seed life. These circumstances might also prevent the microbial community from changing too much while being stored. Therefore, the stability of the seed's associated microbiome should be taken into account in addition to the seed's longevity and physiological quality. In this way, long-term seed conservation involves both microbial management and moisture management.

Harnessing the Seed Microbiome for Agriculture and Conservation

i. Seed Coating and Biopriming

New options to employ beneficial seed-associated microbial species in agriculture through seed coating and biopriming have been made possible by the expanding knowledge of such microbes. These methods involve applying certain beneficial bacteria or fungi to seeds prior to sowing. These microbes can aid in seedling growth, germination, nutrient uptake and defence against environmental stresses and diseases. While biopriming combines controlled seed hydration with microbial treatment, seed coating offers a practical method of delivering microbial inoculants straight to the seed. As a result, these methods can effectively supplement or replace traditional soil-applied microbial treatments (Rocha *et al.*, 2019).

ii. Engineering Heritable Seed Microbiomes

Establishing beneficial microbes in the mother plant so that they can naturally spread to the developing seeds is a more sophisticated strategy. The goal of this concept is to make the relationship between the crop and its beneficial microbial population more stable and maybe self-renewing. Beneficial microbes could be introduced into crop plants and then passed on to their offspring. These methods could eventually help in the development of heritable microbial characteristics, which would eliminate the requirement for repeated microbial administration during each cropping season (Mitter *et al.*, 2017).

iii. Implications for Genebanks and Long-Term Conservation

The seed microbiome provides an additional level of conservation for seed banks that are responsible for maintaining plant genetic resources over many years. The microbial community that accompanies the stored seed is rarely taken into consideration by standard techniques, which place an emphasis on moisture reduction, low-temperature storage and routine viability testing. Understanding how to preserve or purposefully restore, a seed's associated microbiome during long-term storage is becoming an important factor in addition to traditional moisture and temperature management, as interest in restoring damaged ecosystems and enhancing the resilience of reintroduced or regenerated plant populations grows (Chandel *et al.*, 2022).

Conclusion

Seeds are no longer considered simply as dry, self-contained packages of genetic material and food reserves. They also harbour a diverse and largely invisible community of bacteria and fungi known as the seed microbiome. These microorganisms can affect critical processes like seed survival, dormancy, germination, seedling growth, pathogen suppression and tolerance to drought and other environmental challenges. They can be acquired from the surrounding environment or inherited from the mother plant. Additionally, seed longevity and storage are strongly associated with the seed microbiome. The survival and composition of associated microbes are also influenced by temperature and moisture, two important variables that regulate the physiological degradation of seeds. Therefore, future seed-storage research should consider not only maintaining seed viability but also understanding how storage conditions affect beneficial microbial communities.

Future Prospects

The study of the seed microbiome is still an emerging field, offering several exciting opportunities. Advances in metagenomics, high-throughput sequencing, culturing techniques, metabolomics and artificial intelligence will help scientists identify previously unknown microorganisms and understand their functions. To increase germination, vigour, nutrient uptake and stress tolerance, beneficial microbes could be purposefully chosen and delivered by biopriming, microbial seed coating and targeted inoculation. In the longer term, engineering heritable seed microbiomes could allow beneficial microorganisms to be naturally transmitted from one plant generation to the next, reducing the need for repeated microbial application. During long-term conservation, seed banks may also investigate strategies for maintaining or reestablishing significant microbial ecosystems. Therefore, the idea of a "high-quality seed–microbiome system" may replace the notion of "high-quality seed" in the future of seed science. Developing climate-resilient crops, lowering chemical inputs, enhancing seed performance, and preserving plant genetic resources might all be accomplished sustainably by utilizing these hidden microbial companions. Therefore, the tiny microbes found in seeds could be a valuable biological resource for sustainable agriculture in the future.

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