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Healthy Seed, Healthy Crop: Why Seed Health Matters for a Better Harvest

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A healthy and vigorous seed is the foundation of a productive crop, yet seed health is often overlooked compared with other crop-management practices. Seeds can harbour or acquire a range of harmful fungi, bacteria, viruses and insects during crop production, harvesting, processing and storage, and these hidden threats can impair germination, seedling vigour and crop establishment. Poor seed health may lead to delayed and uneven emergence, seedling mortality, gaps in crop stand and increased production costs. At the same time, seed performance is influenced not only by germination but also by vigour, genetic and physical purity, moisture content, storability and the presence of beneficial microorganisms. This article highlights the importance of seed health as the first link in the crop-health continuum and discusses the major factors affecting seed quality from production to sowing. Emphasis is given to seed-borne pathogens, insect damage, seed–soil interactions and the importance of seed vigour under variable field conditions. Practical approaches for maintaining and improving seed health, including quality-assured seed, seed health testing, appropriate storage, seed treatment, seed priming, biopriming and beneficial microbial interventions, are discussed. The emerging role of seed-associated microbiomes, advanced imaging, molecular diagnostics and other innovative technologies in developing high-performance and stress-ready seed is also highlighted. Integrating sound seed-health practices with appropriate field management can provide rapid and uniform crop establishment, reduce early crop losses and improve resource-use efficiency. Protecting seed health at the beginning of the production cycle therefore represents a simple yet powerful strategy for building healthier, more resilient and productive crops.

Keywords: Seed health, seed quality, seed vigour, seed-borne pathogens, seed treatment.

Introduction

A successful crop begins long before the first green leaves appear above the soil. It begins with a seed. Although seeds are small, they carry the potential to produce an entire crop and ultimately contribute to food, nutrition and farm income. Every plant in a field starts its life as a seed, and the condition of that seed can influence what happens throughout the crop season. For this reason, seed quality and seed health should be regarded as the foundation of successful crop production. Farmers generally pay considerable attention to land preparation, sowing time, fertilizers, irrigation, weed management and insect pests once the crop is established. However, an equally important question is often overlooked: What is the health of the seed being planted? Even when the soil is fertile and all other management practices are followed properly, poor-quality seed can result in unsatisfactory crop establishment. A healthy seed, on the other hand, can germinate quickly, produce a strong seedling and

establish a uniform crop stand, giving the crop a better start from the very beginning. Seed quality is a broad concept that includes germination, vigour, genetic purity, physical purity, moisture content, storability and seed health. Among these attributes, seed health has a special importance because it directly connects the seed with pests and diseases. A seed may have good size, attractive appearance and acceptable germination, yet it may still carry harmful organisms that can affect its performance after sowing. Thus, simply looking at a seed is not always enough to determine whether it is truly healthy (Sundareswaran et al., 2023).

Seed health refers broadly to the absence or safe management of harmful organisms associated with seeds and the maintenance of the seed's physiological ability to perform normally. Seeds can harbour a wide range of harmful organisms, including fungi, bacteria and viruses, either on their surface or within their tissues. Some pathogens may remain associated with the seed without producing any obvious symptoms. When such seeds are sown under favourable environmental conditions, the associated pathogens may become active, causing seed decay, poor germination, seedling death or disease development in the emerging crop (Vishunavat et al., 2023). The problem can sometimes begin even before the seed reaches the farm. During crop development, pathogens and insects may attack flowers, pods, fruits or developing seeds. Such attacks can interfere with seed formation and filling and may result in poorly developed or infected seeds. After harvest, improper drying and storage can further accelerate deterioration. Excess moisture, high temperature, poor ventilation and insect infestation can favour the development of storage fungi and other pests. Consequently, seed health is influenced by the entire journey of the seed—from production in the field to harvesting, processing, storage and finally sowing. The effects of unhealthy seed are not restricted to reduced germination. Infected or deteriorated seeds may germinate slowly and produce weak seedlings. Such seedlings often emerge unevenly, resulting in gaps in the field and an irregular crop stand. Poor establishment can make it difficult for the crop to use available sunlight, water and nutrients efficiently. It may also increase competition with weeds and make the crop more vulnerable during the early stages of growth. In severe situations, farmers may even be forced to undertake gap filling or re-sowing, increasing production costs and wasting valuable time.

Seed: More Than Just a Planting Material

A seed is a remarkable biological package that contains everything needed to begin the life of a new plant. Inside its protective covering lies the embryo—the young plant in its earliest form—along with stored food reserves that provide energy during the initial stages of germination and seedling growth (Bewley and Black, 2014). When a seed receives suitable moisture, temperature and oxygen, these reserves support the emergence of the root and shoot, allowing the young plant to establish itself in the soil. However, not every seed has the same ability to perform this task successfully. Seeds may differ in their physical condition, maturity, genetic identity, physiological quality and health status. Therefore, for farmers, a seed should not be judged simply by its appearance or size. A truly high-quality seed should have good physical and genetic purity, high germination, strong vigour, appropriate moisture content, good storability and freedom from important seed-borne pests and pathogens. Germination is one of the most familiar indicators of seed quality. It refers to the ability of a seed to resume growth and produce a normal seedling when provided with favourable conditions. A seed lot with high germination generally provides a better chance of achieving the desired plant population in the field (Matthews et al., 2012). However, germination alone does not tell the complete story. Two seed lots may show similar germination percentages under ideal laboratory conditions but behave very differently after sowing in the field. One may emerge quickly and uniformly, while the other may emerge slowly and produce weak seedlings. This difference becomes particularly important when field conditions are not ideal, such as during periods of low or excessive soil moisture, temperature fluctuations, soil crusting or early-season pest and disease pressure.

This is where seed vigour becomes important. Seed vigour reflects the overall strength and performance potential of a seed lot. Vigorous seeds generally germinate rapidly, produce uniform emergence and develop stronger seedlings, giving the crop a better start. High-vigour seeds are particularly valuable under challenging field conditions because they can establish more quickly and make better use of available water, nutrients and sunlight during the early stages of growth. Rapid and uniform establishment can also reduce gaps in the crop stand and help seedlings pass through their most vulnerable stage more successfully. Thus, while germination answers the question "Can the seed produce a normal seedling?", vigour provides a broader indication of "How quickly, uniformly and strongly can the seed establish under practical field conditions?" Seed health adds another essential dimension to seed quality. A seed may have good germination and apparently normal appearance but still carry harmful fungi, bacteria, viruses or other organisms on its surface or within its tissues. Such hidden infections may not be detected by simply looking at the seed and may become active after sowing, particularly when environmental conditions favour disease development. Infected seeds can result in seed decay, poor emergence, weak seedlings and the introduction of pathogens into new fields. Therefore, germination, vigour and health should not be considered separately; they work together to determine the true planting value of a seed lot. In simple terms, a good seed is not merely one that germinates—it is one that is healthy, vigorous and capable of producing a strong plant under real field condition

Importance of seed health

The importance of healthy seed becomes even greater under the increasingly variable climatic conditions experienced by agriculture. High temperatures, irregular rainfall, excessive moisture, flooding, drought and sudden changes in temperature can create additional challenges for germinating seeds and young seedlings. Excess moisture, for example, may favour several seed- and soil-borne pathogens, while drought or high temperature can reduce seedling growth and weaken the plant's ability to cope with additional stresses. When a seed already has poor physiological quality or carries harmful organisms, these environmental stresses can further reduce its ability to establish successfully. Biotic stresses—including diseases caused by fungi, bacteria and viruses and damage caused by insects and other pests—can affect seeds at different stages of their life cycle. Some pathogens are transmitted directly through seed, while others reach the seedling from contaminated soil or crop residues. Insects can damage developing seeds in the field or stored seeds after harvest. These interactions demonstrate that seed health cannot be considered separately from crop health. The health of the seed is the first link in the chain of crop health (Afzal et al., 2026).

At the same time, seeds are not biologically inactive structures. They interact with their surrounding environment and with a diverse community of microorganisms. While some microorganisms are harmful, others can be beneficial. Certain bacteria and fungi associated with seeds and roots can promote plant growth, compete with harmful organisms and stimulate natural defence mechanisms in plants. This emerging understanding of the seed-associated microbial community is opening new possibilities for improving seed health through biological approaches such as biopriming and beneficial microbial treatments. Modern seed science is therefore moving beyond the traditional question of "Will this seed germinate?" Researchers and seed technologists are increasingly asking broader questions: How quickly will it germinate? How vigorous will the resulting seedling be? Is the seed carrying a pathogen? Can it withstand environmental stress? Does it harbour beneficial microorganisms? And can its performance be improved before sowing? These questions are particularly important as agriculture seeks to produce more food with fewer resources and under increasingly unpredictable growing conditions.

Fortunately, several approaches are available to protect and improve seed health. The use of quality-assured seed, proper harvesting and drying, hygienic processing, appropriate storage and regular seed health testing can prevent many problems before sowing. Seed treatment can provide protection against important seed-borne and soil-borne pathogens, while seed priming can improve the speed and uniformity of germination. Biological seed

treatments and beneficial microorganisms are also gaining attention as environmentally friendly approaches to strengthen seed performance and crop establishment. Thus, seed health is much more than simply achieving a high germination percentage. It represents the ability of a seed to remain healthy, vigorous and capable of establishing a strong plant in the field. A healthy seed provides the crop with a strong beginning, while an unhealthy seed can carry problems into the field even before the farmer sees the first symptoms.

Table 1. Major components of quality seed and their importance

Seed quality component	What it means	Importance in crop production
Genetic purity	Seed belongs to the intended variety	Ensures desired crop characteristics and uniformity
Physical purity	Freedom from inert matter, weed seeds and other crop seeds	Provides a clean and uniform seed lot
Germination	Ability to produce normal seedlings	Ensures adequate plant population
Seed vigour	Speed, uniformity and strength of seedling development	Helps rapid and uniform crop establishment
Seed health	Freedom from important seed-borne pests and pathogens	Reduces disease transmission and seedling mortality
Moisture content	Amount of water present in seed	Influences storage life and deterioration
Storability	Ability to retain quality during storage	Ensures planting value until the next season

The Hidden Enemies Travelling with Seeds

One of the greatest challenges in seed production is that harmful organisms can remain hidden within or on seeds. Fungi are among the most common seed-associated organisms, while bacteria and viruses can also be transmitted through seed in several crops.Seed-borne pathogens may remain inactive during storage but become active when environmental conditions become favourable after sowing. Infected seeds may fail to germinate, decay in the soil or produce weak seedlings. In some cases, infected seedlings emerge normally but later develop disease symptoms (Gebeyaw, 2020). The problem does not stop with the individual seed. An infected seed can introduce a pathogen into a previously clean field. Once established, the pathogen may spread from plant to plant and eventually affect crop yield and seed quality. This makes seed health particularly important for diseases that are difficult to control after they become established in the field.

When Insects Attack Seeds

Seed health is not restricted to microorganisms. Insects can also influence seed quality directly and indirectly. Insects feeding on developing seeds may reduce seed filling, alter nutrient reserves and produce poorly developed seeds. In storage, insect infestation can cause physical damage, weight loss and deterioration of seed quality (Mahapatra et al., 2019). The effects of insect attack may extend beyond visible damage. Seeds developed under severe insect pressure can show reduced germination, lower vigour and altered biochemical characteristics. For example, sap-sucking insects such as aphids can interfere with the normal development of reproductive structures and developing seeds**.** Thus, the health of the seed may reflect what happened to the mother plant during crop development.

The Seed–Soil Battlefield

The moment a seed is placed in the soil, it enters a complex biological environment. Millions of microorganisms are present around the seed, including both harmful and beneficial organisms. Harmful soil-borne pathogens can attack the seed during imbibition or infect the

emerging root and shoot. Poor drainage, excessive moisture and unsuitable sowing conditions may increase the risk of seed and seedling diseases (Gupta and Kumar, 2020). At the same time, beneficial microorganisms can colonize the seed and emerging roots. Some beneficial microbes can compete with harmful organisms, produce compounds that suppress pathogens or stimulate plant defence mechanisms. This has led scientists to view the seed not simply as a storage structure, but as an important biological interface between the plant, microorganisms and the soil environment.

Why Seed Vigour Matters Under Stress

A seed may germinate successfully under ideal laboratory conditions but perform differently in the field. Field conditions are rarely perfect. Seeds may encounter excessive moisture, temperature fluctuations, drought, soil crusting, salinity, pests or pathogens (Lamichhane et al., 2018). Vigorous seeds generally emerge faster and more uniformly, giving seedlings a better opportunity to establish before severe stress occurs. Rapid establishment can be particularly valuable when young plants are vulnerable to pathogen attack or insect feeding. Therefore, seed vigour acts as an important bridge between seed quality and field performance.

Seed Treatment: Protecting the Crop from the Beginning

Seed treatment is one of the most practical approaches for protecting seeds and seedlings from harmful organisms. Depending on the crop and problem, seed treatment may involve fungicides, insecticides, biological agents or other approved products. The major advantage of seed treatment is that protection is concentrated around the seed and emerging seedling, where it is most needed. Compared with repeated field applications, properly designed seed treatments can reduce the quantity of material required and provide early protection. However, seed treatment should always be based on the crop, target pest or pathogen and locally recommended practices. The use of unapproved chemicals or excessive doses can damage germination and may have undesirable effects on beneficial organisms I(Mancini and Romanazzi 2014).

Seed Priming: Giving Seeds a Head Start

Seed priming is another promising approach to improve seed performance. In simple terms, priming involves controlled hydration of seeds so that early physiological processes of germination begin without allowing the seed to complete germination. After drying, primed seeds can often germinate more rapidly and uniformly when sown. Depending on the method, priming may also improve seedling establishment and help plants cope with certain stresses.
Hydropriming, osmopriming, biopriming and other approaches are being investigated for different crops. Among these, biopriming, which combines seed hydration with beneficial microorganisms, is particularly interesting because it can potentially improve both seed performance and biological protection.

Beneficial Microbes: Friends of the Seed

Not all microorganisms associated with seeds are harmful. Seeds and their surrounding environment can harbour beneficial bacteria and fungi that may support plant growth and protection.Beneficial microorganisms can act through several mechanisms. They may compete with harmful organisms for nutrients and space, produce antimicrobial compounds, stimulate plant growth or activate the plant's own defence responses. Recent advances in seed microbiome research have increased interest in using beneficial microorganisms as biological tools for improving seed health. Such approaches could become an important component of sustainable crop production. The future may therefore involve not only protecting seeds from harmful organisms but also deliberately encouraging beneficial microorganisms associated with seeds.

Table 2. Approaches for improving seed health and field establishment

Approach	Main purpose	Potential benefit
Use of certified seed	Ensures quality standards	Better genetic and physical purity
Seed health testing	Detects seed-associated pathogens	Prevents introduction of infected seed
Seed treatment	Protects seed and young seedlings	Reduces early disease and pest damage
Seed priming	Activates early germination processes	Faster and more uniform emergence
Biopriming	Combines priming with beneficial microbes	Improved establishment and biological protection
Proper seed storage	Prevents deterioration and infestation	Maintains germination and vigour
Good field management	Reduces favourable conditions for pathogens	Supports healthy crop establishment
Integrated pest management	Manages pests using multiple approaches	Reduces crop losses sustainably

From Seed Health to Crop Health

The relationship between seed health and crop productivity can be viewed as a chain:

Healthy seed → rapid germination → vigorous seedling → uniform crop stand → better stress tolerance → healthier crop → improved yield and quality

Breaking this chain at the seed stage can have consequences throughout the crop cycle. Poor-quality seed may require farmers to compensate through gap filling, repeated sowing or additional crop management. In contrast, good-quality seed provides a strong starting point. This is particularly important for small and resource-limited farmers, for whom poor crop establishment can result in significant economic losses.

The Future of Seed Health

Seed science is rapidly moving beyond conventional germination testing. Modern approaches are increasingly being used to understand seed quality at physiological, biochemical and molecular levels. Advanced imaging can detect differences in seed size, shape, colour and structural characteristics. Molecular techniques can help identify seed-associated pathogens. Digital tools and artificial intelligence are also being explored for rapid and non-destructive assessment of seed quality. At the same time, research on beneficial microorganisms, biological seed treatments, nanoparticles and novel priming technologies is opening new possibilities for protecting seeds and improving their performance. The future concept is therefore not simply "high-germination seed", but "high-performance, healthy and stress-ready seed."

What Can Farmers Do?

Maintaining seed health does not always require sophisticated technology. Several simple practices can make a major difference:

- Use quality-assured or certified seed from reliable sources.
- Avoid sowing seed that is visibly damaged, mouldy or severely deteriorated.
- Check seed germination before large-scale sowing when there is doubt about quality.
- Follow recommended seed treatment practices for the crop and region.
- Store seed in a cool, dry and clean environment.
- Protect stored seed from insects, rodents and excessive moisture.
- Avoid repeatedly using seed from severely diseased crops.
- Maintain field sanitation and appropriate crop rotation where recommended.
- Use biological seed treatments when they are scientifically validated and locally recommended.

- Follow recommended sowing depth, soil moisture and seed rate to achieve uniform establishment.

Conclusion

A seed may be small, but its importance to agriculture is enormous. It carries the potential for an entire crop and represents the first point at which farmers can influence crop health and productivity. A healthy seed germinates well, establishes quickly and gives the crop a stronger beginning. Biotic stresses such as fungi, bacteria, viruses and insects can compromise seed quality and weaken crop establishment. However, modern seed science is providing new opportunities to protect seeds through improved testing, seed treatment, priming, beneficial microorganisms and emerging technologies. The message is simple: protecting the seed means protecting the crop. Investments made in seed health at the beginning of the season can reduce problems later and contribute to more uniform crops, better resource use and improved productivity. As agriculture moves toward more sustainable and climate-resilient production, the seed will play an increasingly important role. The future of crop protection may therefore begin not with the mature plant, but with a healthy seed placed in healthy soil at the right time.

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