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# Sorghum Seed Health Management: Implications of Legume Intercropping for Seed-borne Fungal Pathogens, Seed Quality and Longevity

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***Authors' contributions***

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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## Abstract

Sorghum (*Sorghum bicolor* (L.) Moench) is an important staple crop for food security, income generation, and livelihoods, especially in the semi-arid regions of sub-Saharan Africa. However, seed-borne fungal diseases pose a significant constraint to sorghum productivity by affecting germination, seed vigour, seedling establishment, grain quality, and storage longevity. This review synthesises existing knowledge on sorghum seed health and seed-borne fungal pathogens, and the potential role of sorghum–legume intercropping in influencing fungal infection, seed quality, and storability. Important seed-associated fungi, including *Fusarium*, *Alternaria*, *Curvularia*, *Aspergillus*, *Penicillium*, and *Colletotrichum,* have been reported in sorghum and are associated with reduced seed viability, seedling establishment, grain deterioration during storage, and potential mycotoxin contamination. Sorghum–legume intercropping contributes to seed health management by disrupting continuous host cropping, altering the crop microclimate, enhancing soil fertility, and modifying beneficial microbial communities. However, a thick intercrop canopy could also increase humidity and thus favour fungal growth in certain environments. Although evidence for agronomic services of intercropping is growing, there is a paucity of literature relating specific legume species to seed-borne fungal infection, seed vigour,

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and storage longevity, especially in the semi-arid region of East Africa. Future research should integrate field-based disease assessment, pathogen identification and characterisation, seed quality testing, and storage studies to elucidate these interactions for sustainable sorghum seed health management.

*Keywords:* *Seed-borne fungi; storage longevity; seed health; seed deterioration; sorghum-legume intercrop; pathogen suppression.*

## 1 Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is a staple cereal that contributes substantially to food security, livestock sustenance, and income generation for many households, especially in the semi-arid regions of sub-Saharan Africa. Its relatively high tolerance to drought and other environmental stresses also makes it a suitable crop for smallholder farms in rainfed areas. Despite its economic importance, numerous biotic and abiotic stressors constrain sorghum yield and grain quality. Seed-borne pathogens such as *Fusarium, Alternaria, Curvularia, Aspergillus, Penicillium, Colletotrichum*, and other parasitic and opportunistic fungi are among the most significant constraints on sorghum production. These pathogens adversely affect germination, seed vigour, seedling development, and crop productivity (Ackerma*n et* al., 2021; Cherop & Nyongesa, 2025; Keda*r et* al., 2025). Seed-borne fungal pathogens may occur as external contaminants on the seed coat or internal invaders of seed tissues and can survive between cropping seasons in seeds. Their presence can reduce seed viability and germination, hinder seedling establishment, and decrease the quality and market price of the harvested grain (Ackerma*n et* al., 2021; Moumn*i et* al., 2023; Pro*m et* al., 2021). Some fungi can produce mycotoxins, posing food and feed safety risks and causing additional economic losses (Ackerma*n et* al., 2021; Astorec*a et* al., 2019). Generally, seed-borne fungal pathogens can compromise seed health by reducing germination, seed vigour, and seedling establishment, while infected seeds can also serve as sources of inoculum in subsequent crops (Dell'Olm*o et* al., 2023; Gebeyaw, 2020; Vishunava*t et* al., 2023). Recent sorghum seed research likewise identified *Colletotrichum*, *Fusarium*, *Cladosporium*, and *Alternaria* among dominant seed-associated fungi, reinforcing the relevance of fungal diversity to seed health assessment (Dong et al., 2025).

According to Gebeyaw (2020), seed health is a significant factor in crop production because healthy seeds are essential for successful crop establishment, uniform plant growth, and optimum productivity, whereas infected seeds often result in poor field emergence and increased disease incidence (Dell'Olm*o et* al., 2023; Vishunava*t et* al., 2023). In sorghum, seed-borne fungal pathogens are important sources of primary inoculum that reduce seed germination, impair seedling establishment, deteriorate grain quality, and contribute to significant yield losses through diseases such as grain mould and *Fusarium*-associated infections (Ackerma*n et* al., 2021; Pro*m et* al., 2021). Infected seeds can serve as both a survival structure and a primary source of inoculum for new infections (Mart*ín et* al., 2022a; Moumn*i et* al., 2023). Therefore, the effects of fungal infection may extend beyond immediate reductions in germination and vigour because damage to seed tissues and reduced physiological quality may also affect the ability of seeds to retain viability during storage. Seed ageing is an irreversible process involving physiological, biochemical, and structural alterations that progressively reduce germination rate, seed vigour, and seed longevity (Choudhury & Bordolui, 2023; Nadaraja*n et* al., 2023; Vija*y et* al., 2026). Seed longevity is consequently an important component of seed quality, particularly where seed is produced in one season and stored for planting in a subsequent season. In addition to environmental factors such as temperature and moisture, fungal infestation and contamination by storage microbes may accelerate seed deterioration and reduce longevity (Trusia*k et* al., 2023; Ziegle*r et* al., 2021). Storage fungi such as *Aspergillus spp*. and *Penicillium spp*. may grow under favourable conditions and promote further deterioration and mycotoxin contamination of the stored grains (Mancin*i et* al., 2016; Sulaiman & Bello, 2024). Therefore, the maintenance of seed health and physiological quality is fundamental to maintaining adequate plant populations, uniform crop establishment, and subsequent productivity. Recent seed-quality literature also identifies germination and seed vigour as central indicators of seed performance and crop establishment (Shivani et al., 2025).

Sorghum-legume intercropping is a promising sustainable strategy to enhance crop productivity and suppress disease pressure. Intercropping affects host density, growth form of the canopy, access to resources, soil organisms' activity, and microclimate surrounding the crop (Akanm*u et* al., 2023; Maitr*a et* al., 2021; Sithole & Olorunfemi, 2024). The introduction of non-host legume species could disrupt pathogen dispersal pathways and reduce the spatial continuity of susceptible sorghum plants (Dell'Olm*o et* al., 2023; Kuya*h et* al., 2021; Namatshev*e et* al., 2024). Legumes can also enhance soil fertility, microbial diversity, biological suppression of pathogens, and crop nutrition (Banerjee & Van Der Heijden, 2023; Chamkh*i et* al., 2022; Kerma*h et* al., 2017). Thus, legume intercropping may influence sorghum plant health and fungal infection with potential consequences on the health and quality of harvested seeds. However, since dense canopies can increase humidity and leaf wetness, they can induce microclimatic conditions favourable for fungal growth; the effects of intercropping are not consistently uniform. Therefore, outcomes may depend on legume type, planting pattern, crop density, climatic conditions, and pathogen strains (Gerlin*g et* al., 2023; Pambuk*a et* al., 2022). Evidence from sorghum–legume systems indicates that intercropping outcomes vary with the companion legume, crop genotype, and system design, supporting context-specific evaluation of sorghum–legume combinations (Muturiki et al., 2019; Raboin et al., 2025). However, direct evidence linking specific sorghum–legume combinations with seed-borne fungal infection, physiological seed quality, and subsequent storage longevity remains limited, particularly under semi-arid East African smallholder conditions. The present review examined the implications of legume intercropping on sorghum seed-borne fungal pathogens, seed quality, and storage longevity. The review also highlights key gaps and areas for future research. The review contributes to a holistic understanding of the potential role of sorghum–legume intercropping in sustainable sorghum production.

## 2. Methodology

A narrative review was carried out to summarise current published evidence relating to sorghum seed health, seed-borne fungal pathogens, sorghum-legume intercropping, pathogen dissemination, fungal detection and identification, seed deterioration and storage quality. The pertinent scientific literature was retrieved by searching major academic databases and scholarly search engines, i.e., Scopus, Web of Science, Google Scholar, ScienceDirect, PubMed and CAB Abstracts.

The literature search was conducted using a combination of keywords: sorghum, seed health, quality of the seed, seed-borne fungi, seed-associated fungi, fungal pathogens, sorghum-legume intercropping, fungal disease, grain mold, seed storage, and seed viability. The terms were combined with the Boolean operators AND and OR to refine the search. Reference lists of relevant articles were also examined to identify additional studies.

Studies were selected based on their relevance to the review objectives, with priority given to peer-reviewed and recent literature. Results were qualitatively synthesised by analysing the outcomes of various sorghum production systems, legume species, fungal pathogens, geographic locations, and experimental environments. Specific attention was given to evidence relating to disease incidence and severity, pathogen presence, seed infection, germination, seed vigour, seed deterioration, and storage life.

Since the studies included in the review varied widely in design, environmental conditions, intercrop systems, fungal species, detection protocols, and measures of effects, quantitative meta-analysis was not performed. The review further identified gaps in the available evidence, particularly the limited empirical information directly linking sorghum–legume intercropping with seed-borne fungal infection, seed physiological quality, and post-harvest storage performance.

## 3. Effects of Seed-Borne Fungal Pathogens on sorghum seed Health

Table 1 summarises the major seed-borne fungal pathogens associated with sorghum and their implications for seed health. Seed-borne fungi may be present externally as contaminants adhering to seed surfaces or internally as infections within seed coats, endosperm tissues, or embryos (Martín *et* al., 2022a). Their ability to survive on or within seeds enables them to remain viable during storage and transportation, facilitating pathogen dissemination across geographical regions and production systems (Moumni *et* al., 2023).

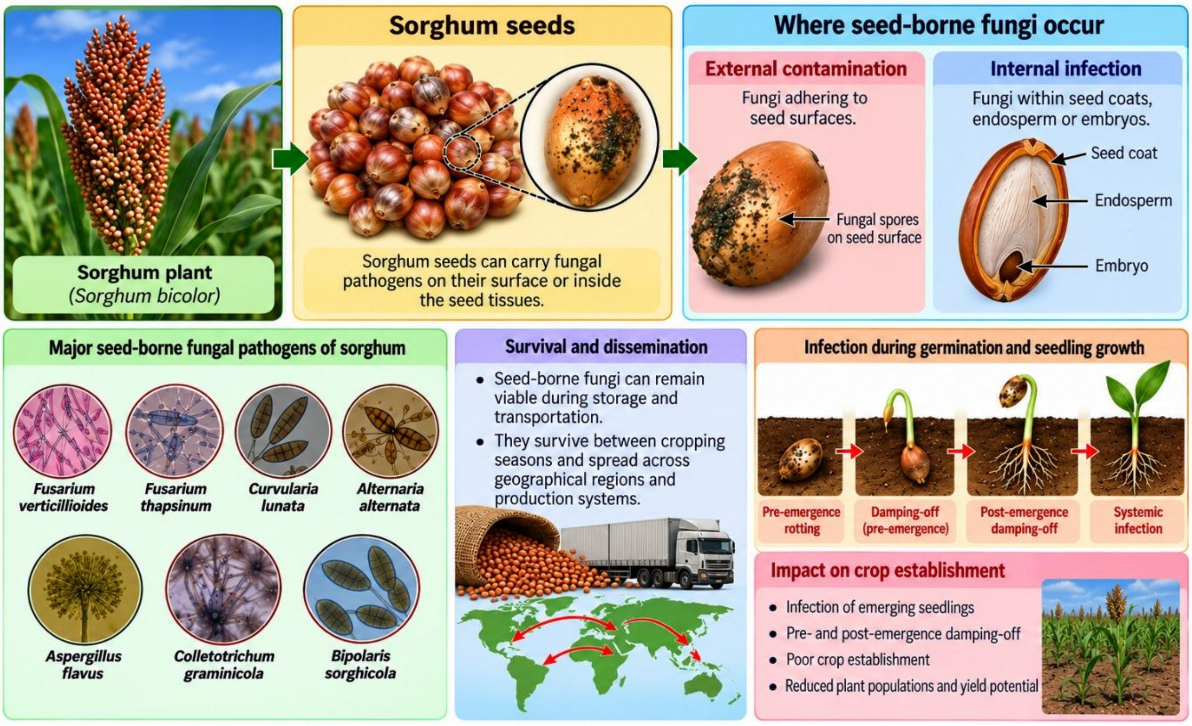


**Fig. 1. Overview of seed-borne fungal contamination in sorghum and its implications for crop establishment and disease spread**

Seed-borne pathogens are important in plant protection because of their dual role as survival structures and inoculum sources (Fig. 1), enabling them to persist between cropping seasons and to initiate disease development in subsequent crops (Brodal & Asdal, 2021; Martín *et* al., 2022a). During germination, seed-borne fungal pathogens can infect emerging seedlings, causing pre-emergence rotting or damping-off, and post-emergence damping-off and other systemic infections, which in turn cause poor crop establishment and reduced plant populations (Dell'Olmo *et* al., 2023). Several fungal pathogens of sorghum, such as *Fusarium verticillioides, Fusarium thapsinum, Curvularia lunata, Alternaria alternata, Aspergillus flavus, Colletotrichum graminicola,* and *Bipolaris sorghicola*, have been reported as important seed-associated pathogens that significantly reduce seed viability and seedling vigour (Ackerman *et* al., 2021; Cherop & Nyongesa, 2025; Kedar *et* al., 2025).

**Table 1. Major seed-borne fungal pathogens of sorghum seed and their implications for seed health**

| Fungus | Association with seed | Disease | Effects on seeds/seedlings | Reference |
|---|---|---|---|---|
| ***Fusarium thapsinum*** | Colonizes developing grain and mature seed | Grain mold; seedling infection | Reduces germination and seed quality | (Cuevas & Prom, 2024) |
| ***Fusarium Verticillioides*** | Internal seed tissues | Grain mold; seed rot/ seedling diseases | Reduces germination and seed vigor- produce fumoisin | (Akhta*r et* al., 2020; Muu*i et* al., 2020) |
| ***Fusarium moniliforme*** | Seed tissues | Grain mold; seedling diseases | Reduced germination and emergence | (Muu*i et* al., 2020) |
| ***Fusarium solani*** | Seed tissues | Seed rot/ seedling diseases | Seedling infections | (Muu*i et* al., 2020) |
| ***Curvularia lunata*** | Seed tissues | Grain mold | Reduced germination/ seedling mortality | (Muu*i et* al., 2020) |
| ***Alternaria alternata*** | Seed surface and tissues | Seed infection/ grain mold complex | Reduced germination and seedling infection | (Monowar*a et* al., 2017) |
| ***Aspergillus flavus*** | Grain/seed-external | Grain mold/storage mold | Reduced germination | (Monowar*a et* al., 2017) |
| ***Aspergillus niger*** | Seed tissues | | Reduced germination and vigor | (Monowar*a et* al., 2017) |
| ***Collectotrichum sublineola*** | Seed tissues | Anthracnose, seedling infection | Reduce establishment | (Akhta*r et* al., 2020; Muu*i et* al., 2020) |
| **Bipolaris sorghicola** | Seed-external | Target leaf spot/ seedling diseases | Seed contamination | (Muu*i et* al., 2020) |
| **Phoma spp** | Seed tissues | Seed infection/ leaf diseases | Reduced seed health | (Akhta*r et* al., 2020; Monowar*a et* al., 2017) |
| **Rhizoctonia spp** | Seed tissues | Seed rot/ seedling diseases | Seed decay and poor seedling establishment | (Muu*i et* al., 2020) |
| **Sporisorium sorghi** | Externally seed-borne | Covered kernel smut | Seedling infection, yield loss | (Mahmou*d et* al., 2019) |
| **Sporisorium reilianum** | Seed-external | Head smut | Smutted panicles | (Zhan*g et* al., 2021) |

Since many fungal pathogens infect sorghum panicles and grains before harvest, cropping systems that alter pathogen populations and disease development may directly affect the health status of harvested sorghum seeds (Ackerma*n et* al., 2021; Pro*m et* al., 2023). Seed-borne fungi may remain dormant within seeds for extended periods and become active when environmental conditions become favourable, a phenomenon that increases the epidemiological importance of seed-borne pathogens because apparently healthy seeds may harbor latent infections that are difficult to detect using visual inspection alone (Martí*n et* al., 2022a). Consequently, seed health testing has become an important component of integrated disease management programmes aimed at reducing pathogen spread and ensuring sustainable crop production (Dell'Olm*o et* al., 2023).

The epidemiological significance of seed-borne fungi is largely attributed to their ability to utilise multiple transmission pathways that facilitate survival, dispersal, and infection. Seed infection may occur before harvest, during harvesting operations, or during post-harvest storage, depending on the pathogen's biology and the prevailing environmental conditions (Moumn*i et* al., 2023). One mode of pathogen transmission is systemic infection of the mother plant, whereby fungal pathogens move through the vascular tissues into developing reproductive structures, resulting in internal seed infection (Dell'Olm*o et* al., 2023). Such infections are particularly important because pathogens become protected within seed tissues and may escape external disinfection treatments. According to Zen*g et* al. (2023), during germination, these internally borne pathogens can infect emerging seedlings and establish systemic infections in subsequent plant generations.

Transmission of seed-borne fungi in sorghum under storage is particularly common for *Aspergillus* and *Penicillium* species. According to Mancin*i et* al. (2016), these storage fungi proliferate under conditions of high temperature and moisture, colonize seeds after harvest, and cause progressive deterioration during storage. Thus, poor storage practices can further facilitate increased pathogen populations and reduced seed quality (Moumn*i et* al., 2023). Seed-borne pathogen transmission is often categorised into seed infestation and seed infection (Blanco & Aveling, 2018).

## 4. Effects of Fungal Pathogens on Sorghum Seed Quality

Seed-borne pathogens generally reduce the germination capacity of seeds. According to Pro*m et* al. (2021), who investigated fungal communities associated with sorghum seeds, fungal infestation with *Fusarium*, *Alternaria*, *Curvularia*, and *Epicoccum* was negatively associated with seed germination rates. The study showed that increased grain mould severity was significantly associated with lower seed germination percentages, suggesting that fungal colonization directly affects seed viability and seedling establishment. A recent study by Cherop and Nyongesa (2025) on the germination performance and fungal diversity in farmer-saved sorghum seeds established that seed lots with higher infestation of *Aspergillus*, *Penicillium*, *Fusarium*, and *Curvularia* generally recorded reduced germination capacity.

Sorghum grain mould has been widely reported to affect sorghum seed germination potential. Grain mould-infected seeds frequently exhibit poor emergence and weak seedling establishment, ultimately affecting field performance and crop productivity (Cuevas & Prom, 2024). According to Ackerman *et* al. (2021), grain mould pathogens, like *Fusarium*, *Curvularia*, *Alternaria*, *Colletotrichum*, and *Aspergillus*, cause poor grain filling, seed deterioration, and reduced germination that affect sorghum seed development and viability. Similar studies have also reported that grain mould infection often results in poor seed filling, deterioration of seed tissues, reduced seed weight, and lower germination rates (Gichile, 2023; Singh *et* al., 2020).

Studies conducted in Africa have reported similar findings. For example, in Ethiopia, Mohammed *et* al. (2022) reported that sorghum seed lots infected with *Fusarium* and *Aspergillus* species had significantly lower germination percentages than pathogen-free seeds. This was largely attributed to fungal degradation of seed tissues and increased seed deterioration during storage. Likewise, studies in Sudan and Nigeria also reported that seed-borne fungi substantially reduced germination and seedling establishment in sorghum production systems, particularly under warm and humid storage conditions that favour fungal growth (Kange *et* al., 2015). Reduced germination capacity by seed-borne fungi is often associated with several pathogenic mechanisms. For instance, fungal pathogens may directly destroy, weaken, or kill embryonic tissues, reduce nutrient reserves required for germination, produce mycotoxins that inhibit metabolic processes, and increase oxidative stress within seeds (Martín *et* al., 2022a). Infected sorghum seeds may also develop pre-emergence damping-off, causing seedlings to fail to emerge from the soil (Lamichhane *et* al., 2017). These effects collectively contribute to poor crop establishment and reduce production.

The contamination of sorghum seeds with fungi during storage reduces seed quality, affecting seed germination and the establishment of seedlings (Martín *et* al., 2022a). Poor germination in turn leads to reduced plant populations and uneven crop stands, which ultimately affects productivity (Dembélé *et* al., 2021). Farmers may incur additional costs through replanting or increased seed rates to compensate for poor field emergence. These additional costs can substantially reduce profitability, particularly among smallholder farmers with limited access to quality seed (Kusena *et* al., 2017; Muui *et* al., 2020). Moreover, seedlings raised from such seeds lack normal vigour, and infected seeds lose their market value due to discolouration and distortion.

Seed-borne fungi have been reported to reduce the processing quality of sorghum seeds for milling by causing endosperm deterioration and discolouration, reducing milling efficiency, and lowering the overall grain quality used for food and feed processing (Ackerman *et* al., 2021). Apart from discolouration, seed-borne fungal infections significantly reduce the processing quality of sorghum grain by causing shrivelling, grain deterioration, and contamination with fungal metabolites (Ackerman *et* al., 2021; Astoreca *et* al., 2019). Grain mould fungi such as *Fusarium*, *Alternaria*, *Curvularia*, and *Aspergillus* species adversely affect the physical appearance of grains, making them less acceptable for human consumption and industrial processing (Khaskheli *et* al., 2025). Fungal colonization can also alter grain composition through degradation of starches, proteins, and lipids, resulting in reduced milling efficiency and lower flour quality (Ackerman *et* al., 2021).

Sorghum seeds infected with fungi may contain fungal toxins; therefore, flour from contaminated seeds may be harmful to human health when consumed (Astoreca *et* al., 2019). This is because some seed-borne fungi produce mycotoxins that compromise food safety and marketability. For example, *Aspergillus flavus* produces aflatoxins, while several *Fusarium* species produce fumonisins and other toxic secondary metabolites in cereal grains (Ackerman *et* al., 2021; Probst *et* al., 2010). Mycotoxins reduce the suitability of sorghum grain for food, feed, brewing, and industrial applications and may result in rejection of grain in local and international markets. Such quality losses reduce farmer income and increase post-harvest economic losses (Munkvold, 2017). Globally, approximately 25% of food crops are estimated to be contaminated with mycotoxins, with cereals such as sorghum being highly susceptible under warm and humid storage conditions (Eskola *et* al., 2020). In Kenya, for example, up to 37% of sorghum samples have been reported to exceed regulatory aflatoxin limits, with some regions recording contamination levels above the Kenya Bureau of Standards threshold of 10 ppb, making the grain unsafe for consumption and trade (Ssepuuya *et* al., 2018). Such contamination results in economic losses through rejection of grain, reduced market value, and increased health risks associated with chronic exposure.

## 5. Effects of Fungal Pathogens on Sorghum Seed Deterioration During Storage

Seed deterioration is a complex and irreversible process involving physiological, biochemical, and structural changes that progressively reduce seed quality, viability, and vigour during storage (Choudhury & Bordolui, 2023). In sorghum, seed deterioration is characterised by reduced germination, impaired seedling emergence, membrane degradation, lipid peroxidation, enzyme inactivation, and depletion of food reserves (Nadarajan *et* al., 2023; Vijay *et* al., 2026). These changes are often associated with oxidative stress caused by the accumulation of reactive oxygen species (ROS), which damage cellular membranes, proteins, nucleic acids, and other essential cellular components (Dahuja & Yadav, 2026). Several factors are reported to influence fungal proliferation, seed deterioration, and storage longevity (Table 2). Reports indicate that seed deterioration in sorghum is influenced by genetic factors, maturity at harvest, storage conditions, and microbial colonization (Mbughi *et* al., 2024; Vijay *et* al., 2026). According to Maurya and Syed (2025), sorghum seeds stored under suboptimal conditions experience increased membrane permeability and electrolyte leakage, which are considered reliable indicators of seed ageing. As deterioration progresses, the seeds eventually lose their ability to withstand environmental stresses, resulting in poor field establishment and reduced crop productivity (Maurya & Syed, 2025)

Fungal infection accelerates seed deterioration by degrading cellular structures, damaging membranes, increasing respiration, and depleting stored nutrients. Studies have shown that infected seeds often exhibit lower vigour, reduced longevity, and poor storage performance (Abdelfattah *et* al., 2021). Several fungal pathogens associated with sorghum seeds contribute directly to seed ageing and quality deterioration. Fungi such as *Fusarium spp.*, *Curvularia lunata*, *Alternaria alternata*, *Colletotrichum sublineola*, *Aspergillus flavus*, *A. niger*, and *Penicillium* species are commonly associated with seed deterioration (Akhtar *et* al., 2020). These fungi colonize seed tissues and utilise stored carbohydrates, proteins, and lipids, resulting in reduced seed weight, viability, and germination capacity (Prom *et* al., 2021).

**Table 2. Factors influencing fungal proliferation, seed deterioration and storage longevity**

| Factor | Influence on fungal pathogen | Influence on seed deterioration | Reference |
|---|---|---|---|
| Moisture content | High-promote spore germination and growth of fungi | High-accelerate respiration, metabolic activity and loss of viability Low-prolong storage life of orthodox seed | Zhou *et al*.m 2020 |
| Storage temperature | Warm-favour fungal growth and multiplication | High-accelrate respiration, oxidative dmage and physiological aging-reduce germination, vigor and longevity | Walters, 2008; Zhou *et al*., 2020 |
| Relative humidity | High- favours fungal growth | High-accelerate ageing and reduce seed vigor and viability | Hay *et al*., 2022; De Vitis *et al* 2020 |
| Initial fungal infection | Seed carries viable inoculum | Damage seed tissues and utilizes stored reserves and accelerate loss of germination and seed vigor | Muui *et al*., 2020; Dutta *et al* 2022 |
| Storage duration | Longer-favor fungal contamination and proliferation | Longer-Reduction in germination and vigor | Dutta *et al*., 2022; Zhou eta l., 2020 |
| Mechanical damage | Cracks and injuries provide entry points for fungal pathogens and increase susceptibility of seed to infections | Damaged seed-increased respiration and susceptibility to pathogens; disrupts protective seed structures | Dutta *et al*., 2022; Fleurat-Lessard 2017 |
| Insect infestation | Damage seed tissues and facilitate secondary fungal invasion | Feeding damage causes direct loss of seed reserves and accelerates deterioration, reducing germination | Fleurat-Lessard 2017 |
| Seed maturity and initial quality | Immature and physiologically weak seeds are more vulnerable to fungal invasion and deterioration | Seeds harvested at physiological maturity and with high initial quality maintain viability longer during storage | Walters, 2008; Zhou *et al*., 2020 |
| Storage material and packaging | Permeable materials allow seed to absorb moisture, hence fungal growth | Proper packaging accelerates seed ageing and reduces longevity | De Vitis *et al*., 2020; Solberg *et al*., 2020 |

Storage fungi such as *Aspergillus* and *Penicillium* are particularly important because they remain active during storage and can proliferate rapidly under favourable environmental conditions. Their growth not only accelerates deterioration but may also lead to contamination with mycotoxins such as aflatoxins, which further compromise seed quality and safety (Ziegler *et al*., 2021). In a study done by Kange *et al*. (2015), sorghum grains stored under warm and humid conditions were found to be heavily colonized by storage fungi such as *Aspergillus* spp. and *Penicillium* spp., which were associated with reduced seed germination and seedling vigour as well as increased risk of mycotoxin contamination, leading to significant deterioration in grain quality. According to Ziegler *et al*. (2021), fungal invasion stimulates increased respiration and heat generation within stored grain, accelerating ageing processes and shortening storage life. Pathogen-induced deterioration may also weaken seedling vigour by damaging embryonic tissues and reducing the efficiency of reserve mobilization during germination (Abdelfattah *et* al., 2021). Consequently, infected sorghum seeds often produce weak seedlings that are more susceptible to environmental stress and secondary pathogen attack.

## 6. Implications of Legume Intercropping for Seed-Borne Fungal Pathogens, Seed Quality and Longevity

Intercropping refers to an agricultural practice of growing two different crops simultaneously in the same space to make use of the available resources (Maitra *et* al., 2021). This practice is common among smallholder farmers in sub-Saharan Africa, particularly for sorghum-based intercropping systems (Maitra *et* al., 2021). Sorghum-legume intercropping is one of the most widely practised cropping systems in semi-arid regions of Africa, Asia, and Latin America because of its contribution to food security, yield stability, resource-use efficiency, and soil fertility improvement (Akanmu *et* al., 2023; Sithole & Olorunfemi, 2024). The most common legume crop combinations include cowpea, groundnuts, beans, green gram, pigeon pea, lablab, and pulses (Kuyah *et* al., 2021; Namatsheve *et* al., 2024). Table 3 highlights selected studies examining sorghum seed-associated fungi, seed quality and/or intercropping. The potential mechanisms by which legume intercropping may suppress or promote fungal infection of sorghum seed and influence subsequent seed quality and storage longevity are conceptualised in Fig. 2. Sections 6.1 to 6.3 highlight important findings on the influence of legume intercropping on sorghum seed-borne pathogens, seed quality, and longevity during storage.

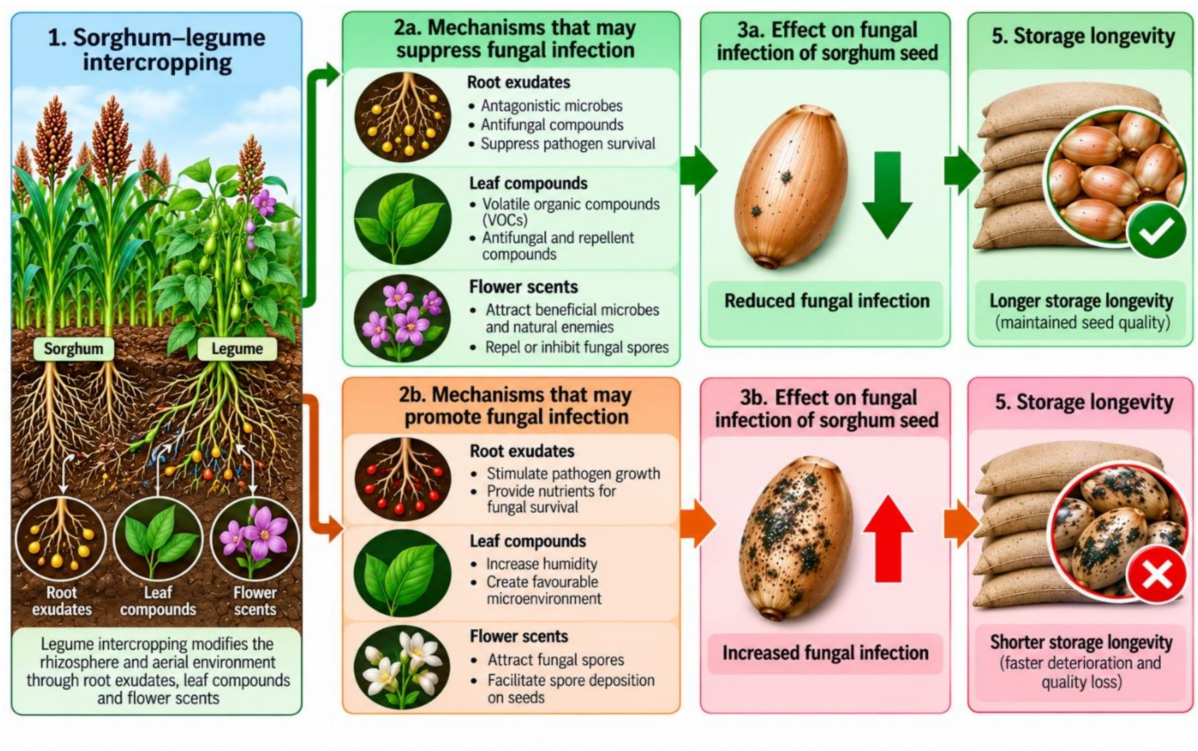


**Fig. 1. Potential mechanisms by which legume intercropping may suppress or promote fungal infection of sorghum seed and influence subsequent seed quality and storage longevity**

### 6.1 Influence of Legume Intercropping on Sorghum Seed-Borne Pathogens

An important mechanism through which sorghum-legume intercropping may influence seed health is the reduction of disease pressure within the cropping environment (Kuyah *et* al., 2021; Namatsheve *et* al., 2024). According to Maitra *et* al. (2021), monocropping systems often provide continuous host availability and favourable conditions for pathogen multiplication and spread. In such systems, disease development is usually sustained by high host density and inoculum build-up in monocropped fields. In contrast, intercropping introduces non-host species that interrupt pathogen transmission pathways and reduce the spatial continuity of susceptible sorghum plants, thereby potentially lowering grain infection and subsequent seed contamination (Dell'Olmo *et* al., 2023). Such effects are particularly important for pathogens associated with grain mould diseases, which infect sorghum panicles during grain development and subsequently become seed-borne.

**Table 3. Selected studies examining sorghum seed-associated fungi, seed quality and/or intercropping**

| Study | Location | Legume/intercrop | Fungi assessed | Seed quality/storage parameter | Main finding |
|---|---|---|---|---|---|
| Iqbal *et al*. (2018) | Pakistan | Cowpea, cluster bean and soybean | Not directly assessed | Crop productivity and soil quality | Legume species and planting ratios influenced soil quality and yield attributes, demonstrating the potential of different legumes to modify sorghum production environments. |
| Pambuka *et al*. (2022) | South Africa | Bambara groundnut, cowpea, dry bean and soybean | Plant- and soil-associated fungal communities, including *Fusarium* | Not directly assessed | Intercropping influenced the composition of plant and soil fungal communities; fungal assemblages varied between crops, plant tissues and years. |
| Koima *et al*. (2022) | Lower Eastern Kenya | Cowpea, green gram and pigeon pea | *Colletotrichum sublineola*, *Curvularia lunata*, *Bipolaris cynodontis*, *Alternaria alternata*, *Sporisorium sorghi* | Not directly assessed | Sorghum was commonly grown in mixed systems with legumes, while fungal disease incidence and severity varied across agroecological zones. The study did not directly compare seed-borne infection among intercrops. |
| Yahuma and Ndeda (2023) | Western Kenya | Soybean and dolichos | Foliar fungal diseases | Not directly assessed | The study evaluated disease incidence and severity under soybean–sorghum and dolichos–sorghum systems, including different planting arrangements, highlighting cereal–legume intercropping as a potential non-chemical disease-management strategy. |
| Muui *et al*. (2020) | Kenya | None | *Acremonium*, *Alternaria*, *Aspergillus*, *Bipolaris*, *Colletotrichum*, *Fusarium*, *Pythium* and *Rhizoctonia* | Seed pathogen incidence | Diverse fungi were associated with farmer-stored sorghum seed, emphasizing the importance of seed health in smallholder production systems. |
| Pamir *et al*. (2021) | India | None | *Colletotrichum*, *Exserohilum*, *Curvularia*, *Alternaria* and *Aspergillus* | Seed-health testing | Different testing methods varied in their effectiveness for detecting sorghum seed-borne fungi. |
| Cherop and Nyongesa (2025) | Western Kenya | None | *Fusarium*, *Rhizopus*, *Penicillium* and *Aspergillus* | Germination and fungal diversity | Fungal contamination was associated with poorer germination performance in farmer-saved seed. |
| Tena *et al*. (2025) | Ethiopia | None | Seed-associated fungi | Physiological seed quality | Seed source influenced physiological seed quality and associated fungal infection. |
| Khaskheli *et al*. (2025) | Global review | Soybean, cowpea, peanut/groundnut and beans | Major fungal pathogens, including grain mold and stalk/root rot pathogens | Indirect implications for grain and seed quality | The review identifies intercropping and crop diversification as potentially useful components of integrated fungal disease management, but emphasizes that outcomes depend on pathogen biology and cropping conditions. |

Intercropping may also influence sorghum seed health through modification of fungal community structure within plant tissues and surrounding soils. In maize, for instance, recent advances in next-generation sequencing have demonstrated that cropping systems significantly influence fungal diversity and abundance (Wang *et* al., 2021). In a recent two-year sorghum-legume intercropping study in South Africa, Pambuk*a et* al. (2022) revealed that fungal communities in both plant tissues and soils differed according to crop species and growing season. The study identified several dominant fungal taxa, including *Cladosporium*, *Epicoccum*, *Phoma*, *Cryptococcus*, and *Fusarium* species, that persisted across intercrop systems. The findings suggest that intercropping alters fungal community composition and may influence the prevalence of both beneficial and pathogenic fungi associated with sorghum plants and seeds. The study further showed that plant-associated fungal communities were more diverse than soil communities, indicating complex plant–microbe interactions within intercropping systems.

Leguminous crops release diverse root exudates that influence microbial recruitment and activity in the rhizosphere, and changes in rhizosphere microbial communities may further contribute to improved sorghum seed health (Chen & Liu, 2024; Sharm*a et* al., 2023). Increased microbial diversity often enhances biological suppression of plant pathogens through various mechanisms, including competition for nutrients, antibiosis, hyperparasitism, and induced systemic resistance (Andargie & Zewdie, 2023). Studies have shown that legume-based cropping systems can suppress populations of pathogenic fungi while promoting beneficial microorganisms that contribute to plant health and disease resistance (Banerjee & Van Der Heijden, 2023; Chamkh*i et* al., 2022). Such interactions may reduce fungal infection during grain development and consequently decrease the incidence of seed-borne pathogens in harvested sorghum seeds.

The effects of legume intercropping on sorghum seed health are also linked to improvements in soil fertility and plant nutrition, especially because legumes enhance nitrogen availability and organic matter content in soil (Kerma*h et* al., 2017). According to Nid*a et* al. (2021), improved nutritional status promotes vigorous plant growth and may strengthen plant defence mechanisms against pathogen infection. Studies have shown that healthy sorghum plants are generally better able to withstand fungal colonization and produce seeds with improved physiological quality and vigour (Ackerma*n et* al., 2021; Nid*a et* al., 2021). Thus, enhanced nutrient uptake may generally and indirectly contribute to reduced seed infection and improved seed health outcomes.

Microclimatic modifications within sorghum-legume intercrop canopies may additionally affect fungal infection of sorghum grains and seeds by altering humidity, temperature, light penetration, and air circulation around panicles, thereby influencing the survival, dispersal, and transmission of fungal pathogens (Pambuk*a et* al., 2022). Legume intercrops may also reduce soil splash and lower pathogen dispersal in sorghum fields, thereby decreasing fungal infections in seeds (Boudreau, 2013). However, according to Gerling *et* al. (2023), dense intercrop canopies can also increase relative humidity and prolong leaf wetness, which favours fungal growth and sporulation in crop fields. Generally, the influence of legume intercropping on sorghum seed health may vary depending on intercrop composition, planting density, weather conditions, and pathogen populations (Ackerma*n et* al., 2021).

Several studies have reported improved seed quality parameters in legume-sorghum intercropping systems compared with monocropping systems (Sanf*o et* al., 2023; Ra*d et* al., 2020). Improved nutrient acquisition, enhanced soil biological activity, and reduced disease pressure may contribute to the production of healthier seeds with higher germination percentages and greater vigour (Maitr*a et* al., 2021). Since seed-borne fungal pathogens are among the major causes of seed deterioration, any reduction in fungal infection may positively influence seed viability and storage longevity (Martí*n et* al., 2022a; Solber*g et* al., 2020). Nevertheless, empirical evidence specifically linking sorghum-legume intercropping systems to reduced fungal contamination of sorghum seeds remains limited. In sub-Saharan Africa, where smallholder farmers frequently depend on farmer-saved sorghum seed, understanding the relationship between intercropping and seed health is particularly important. Studies conducted in Kenya, Ethiopia, and South Africa have reported high incidences of seed-associated fungi in farmer-retained sorghum seed lots, often accompanied by reduced germination and seedling vigour (Cherop & Nyongesa, 2025; Koim*a et* al., 2022; Mohamme*d et* al., 2022). Although intercropping is widely practiced in these production systems, relatively few studies have directly examined its effects on fungal infection levels in sorghum seeds under storage. Most available studies focus on crop productivity, nutrient cycling, or soil microbial diversity rather than seed pathology.

## 6.2 Influence of Legume Intercropping on Sorghum Seed Quality

Intercropping may have indirect effects on sorghum seed quality via influences on the crop environment, including soil nutrient content, pathogen interactions, and microbial communities. New findings from a two-year sorghum-legume intercropping trial in South Africa with Bambara groundnut, cowpea, dry bean, and soybean showed that cereal-legume intercropping affected plant- and soil-associated fungal communities, including fungi belonging to the *Fusarium* genus (Pambuk*a et* al., 2022). Such changes may affect the fungal community encountered by developing sorghum grain and, in turn, the health and physiological quality of the harvested seed. Since seed quality is strongly linked to the absence of seed-borne pathogens, reduced fungal infection may lead to enhanced germination, seedling establishment and vigour. Recent sorghum seed research has shown that fungal genera such as *Colletotrichum, Fusarium, Cladosporium* and *Alternaria* are associated with poorer seed health and germination, especially under moisture stress conditions, suggesting that production practices that influence pathogen pressure before harvest could be of significant importance (Muu*i et* al., 2020). Yet, comparative experimental data on the impact of different legume species upon seed-borne fungal infection of sorghum seeds and on physiological seed quality are scarce, representing a significant knowledge gap. Moreover, the effects of individual legume species are also expected to differ, as crops like soybean, cowpea, common bean, Bambara groundnut and lablab differ in canopy architecture, duration of the growing period, extent of root activity, and interactions with soil microbes. Therefore, further research needs to explicitly compare seed harvested from sole sorghum with seed from various sorghum-legume intercrop systems in relation to fungal infection, germination, seed vigour, and seed quality in general.

### 6.3 Influence of Legume Intercropping on Sorghum Seed Longevity under Storage

The effects of legume intercropping on the seed longevity of sorghum are largely indirect and are probably mediated by seed quality/health in the field. Seeds with lower initial fungal infection and higher physiological quality are believed to remain viable for longer in storage, while pre-harvest fungal infection can make seeds prone to faster deterioration. Recent work has demonstrated the significance of initial seed health as well as storage conditions for sorghum longevity. For instance, fungal contamination during storage may negatively impact sorghum seed quality, but biological seed protection maintained germination over 12 months of storage in sweet sorghum (Osorio-Guerrer*o et* al., 2024).

This suggests that pre-storage management practices capable of reducing fungal contamination may have an important impact on maintaining seed longevity. Similarly, a recent study in Northern Ghana reported that delayed harvesting is associated with increased grain mould development and subsequently with reduced germination and seedling vigour after storage but not at harvest, indicating that conditions prevailing in the field before storage may have a considerable impact on the quality of seed post-harvest. Seeds that were harvested later showed significant reduction in germination and seedling vigour after six months of storage, whereas harvesting at physiological maturity enhanced grain quality and storage stability (Azasib*a et* al., 2026). Similarly, recent studies on farmer-saved sorghum seed have shown that fungal contamination can reduce germination, emphasizing the need for proper seed production techniques to obtain healthy seed before storage (Cherop & Nyongesa, 2025). These findings are consistent with the hypothesis that cropping practices that reduce fungal infection during crop production may indirectly enhance seed longevity. Nevertheless, the literature contains limited direct evidence on whether seed produced from sorghum grown in legume intercropping retains viability longer in storage than seed produced in sole cropping. While cereal–legume intercropping is known to affect fungal communities in plant and soil environments, the impact on physiological ageing and storage longevity of harvested sorghum seed is still largely unknown (Pambuk*a et* al., 2022). Yet, it is unclear whether recent evidence directly addresses whether sorghum seed produced from different legume intercrops has greater storage longevity than that from sole cropping. Future work should assess seeds of particular sorghum–legume pairings, including soybean, cowpea, common bean, Bambara groundnut and lablab, for fungal incidence, germination, vigour and longevity under controlled storage conditions.

## 7. Research Gaps and Future Research Priorities

Despite extensive research highlighting the benefits of sorghum-legume intercropping, most research has focused on specific combinations such as sorghum-cowpea and sorghum-soybean. Limited information is available on how legumes such as rice bean, lablab, common bean, and pigeon pea affect the occurrence and severity of major fungal diseases in sorghum. This highlights the need for comparative evaluation of the effects of different legume species on fungal diseases of sorghum under sorghum-based intercropping. Most studies have described disease suppression in intercrop systems qualitatively but have provided limited quantitative measurements of disease incidence, severity, pathogen population dynamics, and yield losses. Few studies have quantified the magnitude of disease reduction associated with specific intercrop arrangements, planting densities, and legume species. There is also inadequate information on disease dynamics in sorghum-legume intercropping systems under the semi-arid environments of Kenya and East Africa, where sorghum is increasingly promoted as a climate-smart crop. Most disease-suppression studies have been conducted in Asia, Europe, or selected African locations. Few studies have explored the impact of intercropping on seed health, seed-associated fungal communities, and post-harvest seed longevity. However, much of the research has concentrated on field disease suppression and yield performance, leaving a gap in knowledge regarding how intercropping might affect the transmission of seed-borne pathogens and improve physiological seed quality during storage. Many investigations prioritise disease incidence and severity assessments without employing morphological and molecular identification techniques to fully characterise the diversity of seed-associated fungi.

The ecological mechanisms by which various legume species alter pathogen populations, soil microbial communities, and crop microclimates to mitigate specific fungal pathogens remain poorly understood. There is also a notable lack of comparative studies assessing the efficacy of different legume intercrops in preserving sorghum seed vigour and longevity under ambient storage conditions. This is particularly critical in sub-Saharan Africa, where issues related to seed deterioration and seed-borne diseases pose significant challenges to sorghum production. The present review demonstrates the significant potential of sorghum-legume intercropping to improve soil fertility, suppress diseases, enhance biodiversity, and promote sustainable crop production. However, several critical knowledge gaps remain, and to advance scientific understanding and improve the practical application of these systems, future research should focus on the following areas: (i) Future research should systematically evaluate different legumes, including cowpea, soybean, common bean, rice bean, lablab, pigeon pea, and groundnut, within sorghum-based intercropping systems. This research should identify which legume species and intercropping configurations are most effective at reducing the occurrence and severity of significant fungal diseases such as anthracnose, leaf blight, rust, grain mould, and smuts. (ii) Detailed field studies are needed to quantify disease reduction under intercropping. Future studies should assess pathogen populations, disease prevalence, severity indicators, infection levels, and crop losses in various intercropping setups. These studies would provide more robust evidence of the efficacy of intercropping as a disease-management strategy.

Future research initiatives should focus on semi-arid areas of East Africa where sorghum serves as a key staple crop. Research conducted under local environmental conditions may yield context-specific recommendations that are directly applicable to smallholder farmers. Future research should explore the impact of sorghum-legume intercropping on seed-borne pathogens, seed vigour, seed germination, seed longevity, and storage quality. Connecting field disease control with post-harvest seed quality will offer a deeper insight into sustainable strategies for reducing seed-borne fungal pathogens while enhancing seed quality, storage life, and overall sorghum productivity.

## 8. Conclusion

The review highlights the critical role of sorghum seed health in sustainable production, emphasizing that fungal pathogens can negatively impact germination, seed vigour, and grain quality. Sorghum-legume intercropping emerges as a promising strategy to enhance seed health by disrupting pathogen spread and improving soil fertility; however, it may also create conditions favourable for disease. Effective management of seed health relies on accurate detection and identification of seed-borne fungi, with traditional methods supplemented by advanced molecular techniques. Despite growing knowledge, there remain gaps in understanding the impact of different legume species and intercrop patterns on seed quality and fungal infections, particularly in semi-arid regions like East Africa. The review advocates for integrated approaches that combine crop diversification, seed health testing, and improved storage practices.

## 9. Limitation

This narrative review is limited by the heterogeneity of the available literature in experimental design, intercrop composition, environmental conditions, pathogen detection methods, and seed-quality measurements. Direct studies linking sorghum–legume intercropping with seed-borne fungal infection and subsequent storage longevity are scarce, particularly for semi-arid East African production systems. Consequently, quantitative meta-analysis was not performed, and several proposed links between intercropping, seed health, and storage performance remain supported primarily by indirect or context-specific evidence. These limitations indicate the need for comparative, standardised field and storage studies.

## Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

## Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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