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Eco-friendly seed treatment strategies for sustainable management of storage fungi in seed crops: A review

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Abstract
Seed storage fungi are among the major constraints affecting seed quality, viability, and food safety during post-harvest storage. Fungal genera such as *Aspergillus*, *Penicillium*, *Fusarium*, *Alternaria*, and *Rhizopus* commonly infest stored seeds under favourable environmental conditions, resulting in deterioration of seed quality, reduced germination, seedling mortality, and mycotoxin contamination. Conventional chemical fungicides are widely used to manage storage fungi; however, their excessive and indiscriminate application has caused in environmental pollution, health hazards, residue problems, and development of resistant fungal strains. Consequently, there is increasing global interest in eco-friendly seed treatment strategies that are sustainable, safe, and effective. Therefore, this review aims to critically evaluate the occurrence and impact of storage fungi in seed crops and summarize recent advances in eco-friendly seed treatment approaches, including plant-based products, biological control agents, physical methods, improved storage technologies, and integrated management strategies. The review also highlights research gaps and future prospects for developing sustainable seed storage systems.

Keywords: Storage fungi, eco-friendly seed treatment, biological control, plant extracts, mycotoxins, integrated management

Introduction

As the largest producer of vital food crops like rice, wheat, maize, groundnuts, and vegetables, India faces a significant challenge in mitigating crop losses caused by pathogen attacks. While farmers often turn to chemical treatments and fungicides to address this issue, these methods can have harmful effects on soil health, human health and the environment. Therefore, it is essential to explore alternative, sustainable solutions that prioritize eco-friendly practices and minimize environmental impact. Seeds play a dynamic role in agriculture, for example 90% of food crops are produced from them. Major cereal crops like rice, wheat, and maize, which are staples in many agricultural zones, are susceptible to various seed-borne diseases. In fact, seeds are often considered the primary basis of crop production, highlighting their importance in ensuring food security and sustainable agriculture (Christiaan *et al.,* 2012) [24].

It has long been recognized that certain fungus can lower seed quality when they infect seeds in the field prior to harvest. However, the effects of additional fungi, referred to as "Storage Fungi," which mostly infiltrate seeds following harvest, were not documented until the 1940s.

Storage fungi that grow on grains or seeds commonly known as storage Molds Grain that is being stored or grain that has spilled on machinery for harvesting, may contain trace amounts of storage fungal spores. This small amount of inoculum can grow quickly in the wrong storage circumstances, causing serious issues. Several key factors leading to the growth of storage fungi in grain, includes moisture levels, temperature, grain condition prior to storage, storage time, and pest activity.

Seed enhancement processes are used to improve performance and resilience, ranging from chemical treatments with fungicides and insecticides to methods like hardening for stress tolerance, nutrient fortification, pelleting for easier handling, infusion with beneficial agents, osmotic priming to boost germination, fluid drilling for precise sowing, and separation of viable seeds to maintain quality. Supporting these, cultural practices such as proper storage, crop rotation, and sanitation help prevent fungal growth, while organic treatments like neem oil and garlic extract offer natural control of seed-borne fungi. Additional options include seed coating, where a protective layer is applied to the surface, and seed pelleting, which encases seeds in material combined with fungicides or other agents to further limit fungal infection.

Impact of Storage Fungi on Seed Quality

Storage fungi refer to a group of fungi that commonly infest stored agriculture products such as grains, seeds, and foodstuffs. These fungi thrive in conditions where there is high humidity, improper storage, prolonged storage periods. *Penicillium* and *Aspergillus* are indeed two of the most common genera of storage fungi, often found in stored crops and commodities. (Sweets *et al.,* 2018) [61] These fungi can thrive in storage environments, leading to spoilage, degradation, and mycotoxin contamination. They also impact grain quality, leading to impaired germinability, undesirable Odors and colour, diminished nutritional content. Seeds and seedlings are visible to a broad range of stresses, including biotic (living) factors, abiotic (non-living) factors, and physiological stresses, which can impact their growth and development (Mastouri *et al*.,2010) [50].

During food storage, seed-borne mycoflora significantly reduce the nutritious content of grains and other food items, creating them unfit for human consumption. They also frequently produce mycotoxins Seed-borne infections can lead to seed rots during germination, causing seedling mortality and ultimately resulting in reduced plant stands and lower crop yields.

When crops fall victim to fungal invaders like *Fusarium, Aspergillus, Alternaria*, and *Penicillium*, the resulting stored crops or end products can become tainted with toxic mycotoxins. To combat this, farmers and storage facilities often turn to antifungal treatments, applying them during crop growth or storage to starve off fungal growth and minimalize the risk of contamination. Reducing the concentration of these antifungal compounds is crucial for food safety because many of them are also hazardous to human health. Prominent scientists are working to find a strategy for preventing fungal growth and mycotoxin production with more environment friendly and health-conscious bioweapons instead of artificial antifungal substances Breakthroughs in biological antifungal treatments have significantly boosted their efficacy in combating fungal species within these genera, resulting in strengthened ecological resilience and environmental protection (Habschield *et al.,* 2021).

Biotic Agents Responsible For Seed Quality Deterioration

a. Seed Borne Fungi

In grain storages, seed-borne fungi are the most prevalent microorganisms, and are commonly grouped into two distinct categories: field fungi, which invade grains during the growing season, and storage fungi, which develop on stored grains under specific conditions (Amare *et al.,* 1995) [3].

1. Field fungi (Ground fungi)

The majority of ground fungal species that penetrate grain seed are parasitic facilitators. This group of fungi is subdivided into three groups. This includes certain pathogens that infiltrate grain that is either growing or mature and may not result in obvious harm. The second group of fungus invades developing grain and is very harmful, while not being specialized. And eventually, those saprobic fungi without specialization that infiltrate wet ripe grain. Cereal grains are susceptible to colonization by various field fungi, such as *Alternaria, Epicoccum purpurascens, Cladosporium cladosporoides, Verticillium lecanii,* and *Fusarium* species. Other notable field fungi that can infect cereal grains include *Aspergillus flavus*, *Penicillium* and *Helminthosporium* (Amare *et al.,* 1995) [3].

2. Storage seed fungi

After grains are harvested and dried to a low moisture level, the dominant fungal population shifts from field fungi to storage fungi, which are well-adapted to thrive in these dry conditions.

These fungi, including *Aspergillus, Penicillium, Rhizopus, Sclerotium* and *Fusarium*. Their growth and ability to produce spores depend on factors like temperature, water availability and gas composition between grains. Understanding how these features interrelate can help develop better grain storage methods to prevent spoilage. Accurately predicting the damage caused by seed-borne fungi is difficult, since the majority of these fungi are saprophytic or only weakly parasitic, making it hard to assess their potential to cause harm (Magan & Lacey *et al.,* 1988) [49].

Important groups of seed storage fungi:

Seed storage fungi are typically categorized into several groups based on their characteristics and the conditions they thrive in. Here are some common groups:

a. **Aspergillus:** Aspergillus is one of the most frequently encountered fungal genera in stored seeds and can notably affect both seed quality and storage life. Species within this genus are widely distributed and are almost always present in stored seed lots, often contaminating seeds during handling and storage (Guchi *et al.,* 2015) [31]. Their presence can lead to reduced germination and lower seedling vigor, and many Aspergillus species also produce mycotoxins that pose health risks to humans and animals (Martin *et al.,* 2022) [47]. The extent of contamination tends to rise over time, with studies showing a marked increase in Aspergillus levels after six to eight months of storage (Olszak-Przybyś *et al.,* 2022). Early detection, along with maintaining low temperature and moisture during storage, is key to limiting its impact, while fungicide treatments can further help control fungal infections (Batzer *et al.,* 2024) [20].

b. **Penicillium:** Penicillium is a common fungus that poses a major risk to seed quality and storage life, as it can infect seeds during harvest, handling, and storage. Widespread in nature, this fungus can significantly compromise seed health, making prevention and control essential (Christensen *et al.,* 1972) [25]. Infections caused by Penicillium often reduce a seed's germination potential, leading to lower sprouting rates, poor emergence, and weak seedling establishment. Affected seeds may also develop off-odors and noticeable discoloration. To limit fungal growth and minimize damage, proper storage management—particularly maintaining low temperature and humidity—is critical (Martin *et al.,* 2022) [47].

c. **Rhizopus:** *Rhizopus* fungi, particularly *Rhizopus stolonifer* and *Rhizopus arrhizus*, can cause significant damage to seeds and crops during storage. These fungi thrive in warm conditions, leading to storage rot and soft tissue decay, and can cause watery leakage, making affected tissues inedible. Furthermore, *Rhizopus* fungi can physically damage seeds and produce mycotoxins, which are harmful to both humans and animals. To minimize the impact of these fungi, it's essential to store seeds under optimal conditions, including low temperature and low humidity, which can help reduce their growth and effects, preserving seed quality and longevity (Anwar &Chatta *et al.,* 2013), (Demissie *et al.,* 2023) [11, 27].

d. **Fusarium:** The *Fusarium* genus of fungi poses a significant threat to seed storage, causing a variety of issues. By producing toxic compounds, these fungi can harm humans and animals, and can infect seeds prior to harvest, leading to decay and reduced quality. In addition*, Fusarium* can cause diseases such as potato dry rot, which infects damaged areas of seed tubers. To effectively manage *Fusarium* in seed storage, it's crucial to detect infestations early, maintain optimal storage conditions, and apply fungicide as needed to stop the spread of these harmful pathogens and protect seed health (Schisler *et al.,* 2000), (Ekwomadu *et al.*,2023) [29, 68].

e. **Alternaria:** Alternaria is a fungal genus and a notable plant pathogen that causes considerable problems in stored seeds across various crops. Under laboratory conditions, it can remain viable and infectious for 15 to 24 months, posing a prolonged risk to seed health. The fungus is typically identified through methods such as agar-plate and seed-blotter tests, and infected seeds often exhibit surface spots that reduce both viability and germination rates. To limit its occurrence, applying fungicides during different crop growth stages can be effective. Proper management of Alternaria is essential for preserving seed quality and longevity (Batzer *et al.,* 2024) [17].

f. **curvularia:** Certain fungi genera pose a significant threat to seed storage, with Curvularia oryzae and Curvularia lunata causing notable damage to stored seeds. Infestation by these species commonly results in discoloration, rotting, shrinkage, and necrosis, which directly lower germination capacity and weaken seedling vigor. Additionally, Curvularia species produce toxic compounds that render seeds unsafe for human and animal consumption. As an effective management approach, botanical fungicides have shown considerable potential in controlling these fungi and reducing storage losses. (Begum & Jayanthi *et al.*,2013), (Buzdar *et al.,* 2023) [18, 19].

"In India, storage fungi pose a significant threat to seed quality and viability. Fungal species like *Aspergillus, Penicillium, Fusarium, Alternaria, and Rhizopus* thrive in the country's warm and humid climate, leading to seed deterioration. To combat this, proper storage techniques are crucial, including cool and dry storage, airtight containers, humidity control, and monitoring seed moisture. Additional measures like fungicides and proper seed processing can also help mitigate the effects of storage fungi, ultimately ensuring better crop yields and food security (Martin *et al.,* 2022) [47].

Table 1: Occurrence of Storage Fungi in Major Seed Crops

Seed Crops	Fungi	References
Ajwain (*Trachyspermum ammi)*	*Aspergillus flavus, A. niger, A. ochraceous, Drechustera australiensis, Fusarium sporotrichiodes, Rhizopus oryzae, Trichoderma viridae.*	(Lal *et al.,* 2013) [45]
Jowar (*Sorghum bicolor*)	*Aspergillus niger, A. flavus, Curvularia lunata, A. fumigatus, Penicillium chryosogenum, F. oxysporum, Helminthosporium pennisetii.*	(Bhusan & Rao *et al.,* 2016) [12]
Maize (*Zea mays)*	*Aspergillus niger, A. flavus, A. terreus, A. candidus.*	(Bhattacharya &Raha *et al.,* 2002) [13], (Rathore & Mathur *et al.,* 2002) [59]
Groundnut (*Arachis hypogaea*)	*A. niger, A. ruber, A. repens, A. versicolor*.	(Bhattacharya & Raha *et al.,* 2002) [13]
Wheat (*Triticum aestivum*)	*Aspergillus niger, Fusarium oxysporum, F. semitectum.*	(Habib & Ahmed *et al.,* 2011)
Rice (*Oryza sativa*)	*Rhizopus stolonifer, Mucor hiemalis, Aspergillus flavus, A. niger, A. candidus, A. fumigates, Penicillium rubrum, P. citrinum, Alternaria alternata, Drecshlera gramini, Curvularia lunata, Trichoderma harzianum, Microdochium lycopodinum, Fusarium oxysporum,*	(Singh & Sinha *et al*., 2016) [66],
Mung bean, Black gram, and chilli *(Vigna radiata, V. mungo, Capsicum annuum*)	*Alternaria alternata, Aspergillus clavatus, A. fumigatus, A. flavus, A. niger, Cladosporium cladosporoides, Cladosporium herbarum, Fusarium oxysporum, Mucor hiemalis, Penicillium citrinum, Rhizopus stolonifer* and *Trichoderma viride.*	(Roy & Ali *et al*., 2023) [58]

Stored grains are susceptible to colonization by a diverse range of fungi, with *Penicillium, Aspergillus*, *Alternaria, Cladosporium, Fusarium, Mucor,* and *Rhizopus* being the most prevalent. These genera bloom in various conditions, making them well-suited to proliferate in grain storage environment. In particular, species such as *Aspergillus niger, A. fumigatus*, *Alternaria alternata, Fusarium moniliformis,* and *Rhizopus arrhizus* are commonly detected in stored wheat. Notably, *Aspergillus niger* is the most often come across species, capable of producing mycotoxins that can compromise grain quality and safety (Mathew & Ahmad *et al.,* 2010) [48].

Seed-borne pathogens that are internally or externally associated with seeds can result in rot, seed abortion, reduction of propagation capacity, and injury to seeds that can lead to systemic or localized infection later in plant growth. A significant portion of the spread of plant diseases in the field that severely reduce agricultural yields are caused by contaminated seeds (Amza *et al.,* 2018) [2].

The manufacture and trading of organic seed have amplified recently, which has increased study of the quality of organic seed and high concerns about the possibility of contamination from seeds containing diseases (Colley *et al.,* 2009) [22].

Leveraging Beneficial Microorganisms: to shield seeds from pathogens and enhance growth. Controlled Atmosphere Storage: Maintaining controlled levels of oxygen, carbon dioxide, and moisture. to slow seed metabolism and prevent spoilage. Cryopreservation: Storage seeds at extremely low temperatures to preserve viability for extended periods. Digital Technologies: Utilizing AI for enhanced traceability and seed storage management. Organic Seed Treatments: Engaging organic-approved ingredients for seed treatments, particularly for certified organic crops. Community-Based Seed Banks: Establishing local seed banks to enhance seed resilience against climate change. These are some of the advancements that aim to ensure food security by preserving genetic diversity and promoting sustainable agricultural practices (Kumar *et al.,* 2024) [40].

Current Status

Preventing storage fungi and maintaining seed health requires controlling moisture, temperature, and physical condition throughout the storage period. For starchy cereals, keeping moisture below 13.5% and for soybeans below

12.5% is critical, since higher levels, especially at elevated temperatures, encourage fungal growth. Moisture can vary within a grain mass, so uniformity is essential to avoid localized hotspots where fungi thrive (Martin & Palmero *et al.,* 2022) [47]. Temperature also plays a key role: growth is slow between 4–10°C but accelerates rapidly at 27–32°C, increasing the risk of spoilage (Magan & Lacey *et al.,* 1998). Damaged creating microenvironments favourable to mold. The acceptable moisture and temperature depend on kernels and foreign material further raise susceptibility by restricting airflow and storage duration, with short-term storage allowing more flexibility and long-term storage requiring stricter control. Prompt drying after harvest to a safe moisture level helps create conditions unfavourable to fungi. Harvesting at the right moisture content, adjusting equipment to reduce kernel damage, and ensuring efficient cleaning all contribute to preserving quality. Thoroughly cleaning machinery, bins, and storage areas before use removes dust, debris, and residual grain that could harbor spores. Pre-storage cleaning to eliminate broken seeds, fines, and other contaminants further improves storability. Aeration helps stabilize temperature and moisture throughout the grain bulk, while regular monitoring and ventilation maintain optimal conditions and allow early detection of insect, mite, or fungal activity.

Eco-Friendly Management of Storage Fungi

The eco-friendly control methods for seed storage fungi is an evolving field, with significant research and development efforts aimed at reducing the reliance on chemical fungicides**.**

It is well known that producing healthy crops and consequently, a larger yield, requires healthy seeds (Sowley *et al.,* 2012) [67]. For crop production, the majority of farmers in emerging nations, however, trust on their own seeds. Therefore, Goal of the study were to determine the native seed storage structures or procedures and how they impact germination as well as the prevalence of infections and pests. The majority of farmers (74%) believed that using traditional storage buildings and techniques was more effective. The survey identified several prominent indigenous storage structures, including as mud silos (boore), gourds, straw baskets, thatch-based "Kanpiles," ceramic pots (dugu), and barns (bugo). The microflora included *Aspergillus flavus, Aspergillus. niger, A. ochraceous, Penicillium sp., Fusarium sp.,* and *Rhizopus stolonifer.* Isolated seed sample fungi detected by agar plate and blotter methods. Still, the majority of farmers in emerging nations grow their own crops using their own seeds. The majority of responders (93%) said they controlled pests and diseases with wood ash and botanicals like neem. The propagation of seeds was reduced by infection. The way that was stored affected germination as well (Sowley *et al.,* 2012) [67].

Koch & Roberts *et al.,* 2014 [41] examined several approaches for managing seed-borne pathogens in vegetables and small grain cereals. The research covered physical methods such as dry heat, hot water, and aerated steam treatments for vegetable seeds, as well as microbial strategies that use beneficial microorganisms to suppress pathogens. It also evaluated natural agent treatments, including plant powders and extracts, as sustainable alternatives for seed protection.

Khan & Tanbir *et al.,* 2018 [42] studied the effects of storage containers, seed storage conditions, and seed moisture levels, on onion seeds and known seed-borne fungi. Sealed containers, lower seeds moisture levels and controlled storage conditions were found to preserve seed quality best, with aluminium foil bags performing best among containers. Mainly *penicillium* and *aspergillus sp*. are rest growing.

Haque *et al.,* 2016 [36] examined how different storage containers, moisture levels, and seed treatments affect the quality of jute seeds. The results indicated that tin pots were most effective in preserving seed quality, followed by poly bags and plastic pots. Seeds stored at the optimal moisture level of 9.5% maintained better quality compared to those stored at the farmer's typical level of 13%. Additionally, seeds treated with Provax-200 performed better than untreated seeds. In contrast, earthen pots showed the poorest results for moisture retention, germination, and overall seed health. Based on these findings, the study recommends storing jute seeds in tin containers with Provax-200 treatment and maintaining the recommended moisture content to ensure better seed quality and viability.

Huigol *et al.,* 2022 Reported that excessive use of agrochemicals poses risks to both human health and the environment, increasing the need for safer, eco-friendly biopesticides. Fungal biocontrol agents such as *Trichoderma* and endophytic fungi present a promising alternative for managing plant diseases while maintaining food safety and minimizing environmental harm. These fungi produce enzymes and secondary metabolites that suppress plant pathogens, trigger the plant's natural defence responses, and compete with pathogens for resources. Current research is focused on utilizing fungi like *Trichoderma* and *Aspergillus* to develop effective biocontrol products. Genetic modification may improve their effectiveness, though further studies are still required. Integrating fungal biocontrol agents with biofertilizers can support more sustainable agricultural practices, despite some practical challenges. Adopting such control measures can help reduce the impact of pathogens on crop yield and quality.

Bello & Sisterna *et al.,* 2010 [16] studied oilseed crops ex. Safflower and groundnut etc. Groundnut, a crop of immense importance in India, contributes significantly to the country's oilseed pool, accounting for around 38% of the total production. With India being the second largest groundnut producer worldwide, after China, crop faces numerous fungal disease threats, impacting its yield and overall production.

Gosh *et al.,* 2018 examined the mycoflora (fungal community) related with seed crops, specifically wheat, rice and maize. Seed samples are collected from various regions where these cereals are commonly grown. To preserve the samples for further analysis, they were dried in the shadow and kept in paper bags at room temperature. He used different methods examples Normal Agar Plate Method, Blotter Method, Rolled Towel Method, Deep Freeze Method. Against *Aspergillus flavus, A. niger, pythium sp., Rhizopus sp., Trichoderma sp*. He studied the impact of 4 chemical fungicides - Topsin, Mancozeb, Antracal, and Dorsal - on seed-borne mycoflora in rice.

According to Raghu *et al.,* 2020 [60], Grain discoloration is an emerging disease that is reducing rice production and productivity by causing yield losses and lowering grain quality. The disease affects rice crops in both field and storage conditions, creating a major threat to farmers' livelihoods. To manage this problem, seed biopriming was tested on the Nua Sugandh Dhan-3 variety. The treatment led to statistically significant improvements ($P < 0.0001$) in germination rate, which reached 90.67%, along with increased seedling length of 30.68 cm, higher seedling vigor scored at 2781.96, and better final crop establishment at 74.09%. Among the treatments, Bacillus subtilis (MH257586) showed strong plant growth-promoting activity, indicating its potential as an effective strategy for controlling grain discoloration.

According to Tripathi *et al.,* 2015 [69] Jute seed trials were conducted to detect seed-borne pathogens using both the blotter method and pure culture techniques. Researchers incubated seeds of jute and mesta, a fiber crop, for 8 days and examined them under a stereo-binocular microscope to identify seed-borne fungi, with further observation using a compound microscope when required. Germination rates differed between the crops, ranging from 0% to 75% in jute and 15% to 100% in mesta. A total of nine fungal species were recorded. The pathogenic fungi included *Curvularia lunata, Alternaria alternata, Macrophomina phaseolina, Bipolaris oryzae, Phoma exigua* on jute, as well as *Fusarium moniliforme and Sclerotium rolfsii* on mesta. Saprophytic fungi detected were *Aspergillus* species on both crops and *Penicillium notatum* on mesta. Infection rates varied from 3% to 33%, with *Phoma exigua* and *Aspergillus* species being the most common.

Singh &Sinha *et al.,* 2016 [66] investigated the presence of seed-borne fungal species in Sahbhagi rice using two methods: Blotter and Agar plate. Rice seeds were stored in diverse conditions, including bins, gunny bags, and were detected at regular intervals (0, 3, 6, 9, and 12 months) to assess fungal growth. To isolate fungi, seeds was surface-sterilized with mercuric chloride ($HgCl_2$) solution or left unsterilized. This allowed researchers to compare fungal growth on sterilized and non-sterilized seeds stored under various conditions. A total number of 16 fungal species including *Aspergillus flavus, A. niger, A. fumigates, A. candidus, Penicillium rubrum, P. citrinum, Alternaria alternata, Rhizopus stolonifer, Drecshlera gramini, Curvularia lunata, Trichoderma harzianum Microdochium lycopodinum, Fusarium oxysporum*, Dark Sterile Mycelium and White Sterile Mycelium were found in the Sahbhagi rice cultivar.

According to Lal *et al.,* 2013 [45] seeds of ajwain collected from major growing area from Rajasthan, identified with various issues such as deformed, discoloured, and insect-damaged seeds, as well as impurities. Fungal spores were detected on the seed surfaces. Seven types of seed mycoflora were identified using Blotter methods and Agar Plate, including *Aspergillus niger*, *Aspergillus flavus,* and *Fusarium sporotrichioides*. The Agar Plate Test showed a higher average incidence of seed mycoflora compared to the Blotter methods. *Aspergillus flavus* was the most common fungus found.

Mahala *et al.,* 2014 [53] found that stored cumin seeds had a higher occurrence of seed-borne fungi. However, using Traditional seed treating material (TSTM) significantly reduced fungal incidence and improved seed germination. The most effective TSTM were: Neem oil, Turmeric powder, Neem leaf powder, Neem seed powder and Mustard oil. These materials lowerence fungal occurrence at different storage periods (2,4 and 6 months) and enhanced seed germination. The study suggests that using TSTM can help control seed borne fungi and improve seed quality in stored cumin seed. Control on these fungi *Alternaria niger, Aspergillus flavus, A. alternata, Curvularia lunata, Fusarium fusarioides, F. pallidoroseum and Rhizopus stolonifer* and *Rhizoctonia solani.*

Khan *et al.,* 2017 [43] conducted a laboratory study to assess how pre-storage fungicide treatments affect onion seeds and the incidence of seed-borne fungi. Five fungicides—Dithane M-45, Bavistin, Homai, Rovral, and Provax-200—were applied to the seeds prior to storage. The results showed that fungicide application significantly lowered fungal incidence and helped maintain seed quality over time. Among them, Bavistin, Provax-200, Rovral, and Dithane M-45 proved most effective in reducing fungal infection and improving germination and seedling vigor. Based on these outcomes, the study recommends these four fungicides for controlling seed-borne fungal infections and preserving onion seed quality during storage. Adopting this approach allows seed producers to supply higher-quality onion seeds, reduce fungal-related losses, and support better crop performance.

Jambhulkar &Kandhari *et al.,* 2007 [39] tested four rice cultivars (Pusa 44, PRH 10, Jaya, and Pusa Sugandh 2) chosen for their optimal seed quality. The study evaluated the efficacy of various seed treatments, including plant extracts, phytochemicals, antagonists, and fungicides. The findings revealed that *Piper betel* leaf extract (0.5%) significantly improved seed germination and seedling vigor while minimizing mycoflora growth, demonstrating its potential as a natural and effective seed treatment.

The research found that *Piper betel* leaf extract (0.5%) was a potent biopesticide against a wide range of field and storage fungi linked to rice seeds. Although higher concentrations of geraniol (1%) and *Calotropis procera* stem extract (1%) showed phytotoxicity, lower concentrations (0.5%) demonstrated beneficial effects. Interestingly, the storage period saw a decline in field fungi (including *Curvularia, Drecshlera, Alternaria, Penicillium, Fusarium, Cladosporium*, and *Trichoconis padwickii*), which were largely replaced by storage fungi (Ali and Deka *et al*.,1996) [10].

Chandel & Kumar *et al.,* 2017 [23] assessed the effectiveness of eleven plant extracts in mitigating storage rot fungi, improving germination rates, and enhancing pea seedling vigor. The extracts, obtained from a range of plants including garlic, Malabar nut, horseshoe vitex, chinaberry tree, Aztec marigold, cannabis, lantana, pepper mint, turmeric, and onion, exhibited considerable antifungal activity against storage rot fungi, such as *Aspergillus sp., Alternaria alternata, A. solani, Phoma sp., and Fusarium spp*. Additionally, the plant extracts showed a beneficial effect on pea seed germination and seedling vigor index, highlighting their potential as ecofriendly seed treatments.

Control Methods

1. Seed Treatment Method

Seed storage fungi can be managed through several treatment methods. Here are some common ones.

Biological Seed Treatment

Applying helpful microorganisms to the surface of seeds prior to planting, like fungi or bacteria, is called a biological seed treatment. By doing this, the seed will likely be covered with advantageous bacteria at planting time, improving the likelihood that the seed and biologicals will form a solid bond. The long-term benefits of biological seed treatments are improved root growth, increased nutrient uptake, enhanced plant vigor (Harman *et al*.,2021) [35].

Biological seed applications refer to seed treatments that rely on natural substances (plant extracts, seaweeds, humic substances protein hydrolysates), or beneficial microorganisms (fungi, bacteria, etc.) to encourage uniform and quick germination of seeds, optimal plant establishment, and crop growth and protection that will improve plant health, yield, and quality.

Biological materials can be coated on seeds utilizing a variety of processes, including film coating, pelleting, seed priming, and liquid formulations. An effective and economical method for physiological seed conditioning and ensuring that the beneficial treatments are available in the spermosphere, endosphere, and rhizosphere (stages of seed) at the crucial "early germination" stages to support healthy and quick development is to apply biological products directly to the seed to improve seed quality and tolerance to biotic and abiotic stress (Sohail *et al.,* 2022) [65].

Table 2: Some examples of biological treatment using plant extract to control storage fungi

Plant Extracts	Seed Crops	Fungi Control	References
Allium cepa L, Allium sativum L, Zingiber officinale Roscoe and Ocimum tenuiflorum, Onion bulb, Garlic Bulb, Ginger rhizome and *Thulasi Leaves*	*Oryza sativa* and *Cajanus cajus*	*Aspergillus niger , A. fumigates, A. terreus Thom, A. Flavus Link, Rhizopus nigricans Ehrenberg, R. Stolonifer*	(Sreelakshmi & Bindu *et al.,* 2018)
Ginger, Garlic, Tulsi, Onion and Neem	Mungbeen seed	*Aspergillus niger, Penicillium rubrum Alternaria alternata and F. moniliformae*	(Singh *et al.,* 2014) [64]
wood, bark and seeds of *Capparis decidua*	*Pongamia* and neem seeds etc.	*Fusarium moniliforme, Aspergillus flavus, A. niger, Penicillium sp. Phytophthora sp., and Mucor spicies.*	(Tripathi *et al.,*2015) [69]
Calotropis procera, Eucalyptus globulus, Datura stramonium Melia azedarach, and *Acalypha indica*	Barley seed	*Alternaria alternata*	(Ahmad *et al.,* 2016) [4]
Citrullus colocynthis fruits and roots, pulp	most seed	*Candida albicans, Fusarium oxysporum, Aspergillus fumigatus* and *Aspergillus niger*	(Hameed *et al.,*2020) [34]
Adhatoda vasica (Malabar nut*), Allium sativum* (garlic*), Melia azadirachta* (chinaberry tree), *Vitex negundo* (horseshoe vitex*), Cannabis sativa* (cannabis), *Tagetes erecta (Aztec marigold), Lantana camera (lantana), Mentha piperata (pepper mint) etc.*	Pea seed	*Aspergillus alternata, Alternaria sp., A. solani, Phoma sp.* and *Fusarium sp.*	(Chandel &Kumar *et al.,* 2017)
Azadirachta indica Lantana camera, the stem extract of *Callistemon rigidus,* The stem extracts of *Datura inoxia, Capsicum annum*, and *Terminalia thorelii* etc.	Paddy field	*Aspergillus niger, Curvularia lunata, Alternaria alternata, Fusarium moniliforme* and *Trichoderma viride.*	(Pawar *et al.,* 2011)

Table 3: Antifungal activity reported of selected essential oils against few storage fungi

S. No.	Essential oil	Controlled fungi	Reference
1	Neem plant (*Azadirachta indica*) leaves, bark and root oil.	*Aspergillus, penicillium, Rhizopus, fusarium,* and *Alternaria spp.*	OGUNSEYE *et al.,* (2022)
2	Garlic (Allium sativum), Neem (Azadirachta indica) Ginger (Zingiber officinale), and Turmeric (Curcuma longa).	*Aspergillus, Fusarium* and *penicillium spp.*	Baba, A. I., & Isa, A.*et al.,* (2024) [20]
3	Garlic (Allium sativum L.), Olive (Oleaeuropaea L.), clove (Syzygium aromaticum L.), Neem (Azadirachta indica L.), Castor (Ricinus communis), and Sesame oil (Sesamum indicum).	*Penicillium digitatum spp.*	Bangulzai & Mushtaq *et al.,* (2022) [21]
4	Cinnamon, Patchouli vetiver, Dill, Origanum and *Cananga odorata*	*Penicillium digitatum spp.*	Zulu & Rao *et al.,* (2023) [70]
5	Garlic cloves and eucalyptus oil.	*Penicillium italicum spp.*	Choudhary, M., Rathore, G. S., & Jat *et al.,* (2024) [26]

The benefits of adding humic substances (HS) to the growing medium of containerized vegetable crops was studied by (Qin & Leskover *et al.,* 2020) [57]. They found that incorporating 1% HS into the plug media enhanced transplant quality by stimulating plant growth, improving root and shoot development, and increasing resilience to drought and heat stress. The study built on existing knowledge of humic acid's optimistic effects on germination and seedling growth, demonstrating the potential of HS as a bio stimulant to promote healthier and more robust plant growth, even under challenging environmental conditions (Qin & Leskover *et al.,* 2020) [57].

A study showcased the benefits of a bio-stimulant by using a coating of seed made from vermicompost and soy flour. which enhanced seed performance under ideal growing conditions. However, additional investigation is wanted to test the effectiveness of such bio stimulant seed treatments and coatings in stressful environmental conditions, as the authors' findings suggest they may hold even greater potential for promoting resilient plant growth when faced with challenges like drought, heat, or other forms of stress (Amirkhani *et al*.,2019) [8].

Chemical Seed Treatment

Chemical seed treatments offer an effective approach for improving crop performance by enhancing emergence and providing protection against soilborne, seedborne pathogens and insect pests. They also help prevent the transmission of seedborne pathogens and reduce the risk of airborne infections, while promoting better crop vigor and uniformity. In addition, these treatments aid in limiting pathogen spread and support compliance with phytosanitary requirements. By using such treatments, farmers can achieve improved crop quality and higher yields while minimizing the environmental impact associated with broader crop protection methods (Munkvold *et al.,* 2014) [51]. Chemical seed treatments include fungicides, insecticides, and seed disinfectants, each serving a specific role in seed protection and performance. Fungicides such as mancozeb and myclobutanil are used to manage fungal diseases, while insecticides help safeguard seeds against pest damage, with examples like Bordeaux mixture commonly applied. Seed disinfectants are also used to improve germination and seedling vigor (Asraf *et al.,* 2005), (Moumani *et al.,* 2023) [19]. A widely adopted practice in integrated crop management is treating seeds with systemic fungicides, which offers benefits like improved plant vigor, better emergence, and protection against both soil-borne and seed-borne fungal pathogens (Lamichhane *et al.,* 2020) [46].

Initial chance to obtain seed excellence occurs while the seeds are attached to the parent plant. Applying chemical defoliants can hasten the maturation and drying process of corn seeds, reducing the risk of quality degradation due to early frost. A specific chemical defoliant can influence the movement of oil bodies within the seed cells, a crucial step in achieving viability and Vigor. By manipulating this process, seed quality can be improved, setting the stage for healthier and more robust seedlings (Dean *et al.,* 2021) [28].

Physical Seed Treatment

When compared to traditional chemical-based treatments, physical techniques of improving plant production have advantages. Recent breakthroughs allow for a comprehensive understanding of physical seed treatments' impact on multiple levels, from morphological changes to molecular responses. Two standard methods are magneto-priming and irradiation. Magneto-priming, an innovative, low-cost, and environmentally friendly approach, leverages magnetic fields to boost crop production, vigor, and seed germination. IRs, including γ- and X-rays, hold significant potential in agricultural and food technologies. Notably, low-dose gamma radiation has been found to enhance productivity and crop performance (Araújo *et al.*,2016) [6].

Example:

Several physical seed treatments have shown promise in improving germination, vigor, and overall crop performance. Magneto-priming, first explored by (Krylov & Tarakanova *et al.,* 1960) [44], demonstrated that magnetic fields can influence plant growth through a phenomenon known as magneto-tropism, essentially acting like a growth regulator for germinating seeds. Later studies, such as those by (Baby *et al.,* 2011) [14], found that applying static and electromagnetic fields can enhance seed germination rates and yield. Ionizing radiation is another widely used technique in agriculture and food technology, helping to control microbial contamination and extend shelf life, which supports both food safety and storage quality (Jayawardena & Peiris *et al.,* 1988) [38]. Exposure to ultraviolet radiation, particularly UV-A and UV-C, has also been reported to improve seed germination and health, though the exact molecular mechanisms are still being investigated (Araujo *et al.,* 2016) [6]. In addition, microwave seed treatment provides a chemical-free method for disinfection and weed control by heating seeds and soil to around 80°C, making it a useful eco-friendly option for greenhouses, nurseries, and horticulture (Bera *et al.,* 2022) [15].

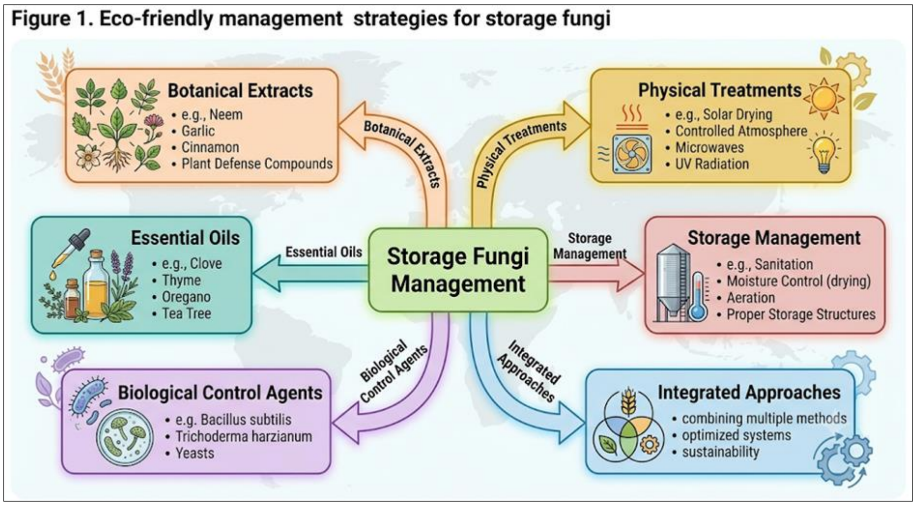

Fig 1: Eco-friendly management strategies for storage fungi

Emerging Trends and Future Perspectives

The seed treatment industry is advancing quickly with new technologies aimed at enhancing seed quality, boosting yields, and reducing environmental impact. Current trends include biological treatments that use beneficial microbes to manage pests and diseases, nanotechnology for the precise delivery of active ingredients, and data-driven precision agriculture to optimize both treatment and planting. There is also a strong shift toward sustainable, eco-friendly formulations and the use of digital platforms to make seed treatment processes more efficient and traceable. These developments are geared toward making seed treatment more effective and sustainable, supporting global food security and environmentally responsible farming. In terms of coating technologies, recent overviews have covered five main methods: dry coating, seed dressing, film coating, encrusting, and seed pelleting. For organic certification, all treatments must meet strict standards regarding approved active ingredients, binders, fillers, and coating materials. This is especially important for sensitive biological agents like entomopathogenic fungi, which require formulations that preserve their viability. Conventional methods involving hydration and dehydration often reduce the effectiveness of these fungi, making traditional techniques such as dressing, film coating, encrusting, and pelleting unsuitable. As a result, innovative dry-coating approaches have emerged as the preferred solution for applying these microorganisms to seeds, helping to advance sustainable agricultural practices (Afjal *et al.,* 2020) [9].

Research Gaps

1. **Limited field-scale validation of botanical seed treatments:** Most work on plant-based extracts has been done in controlled lab settings. Their consistency and effectiveness still need to be tested across diverse field environments and farmer practices.

2. **Insufficient information on the long-term stability of microbial formulations:** Microbial products often lose activity over time during storage and handling. More research is needed on how to maintain their viability and performance for extended periods under practical conditions.

3. **Lack of standardization in essential oil concentrations:** The strength and composition of essential oils vary with source and extraction methods, leading to inconsistent results. Clear standards for dosage and application are missing across studies.

4. **Limited studies on integrated eco-friendly storage systems:** Current research usually looks at single methods like biological agents or natural compounds in isolation. There's a gap in evaluating combined, low-cost systems that can work together for safe storage.

5. **Inadequate economic analyses of biological treatments:** While biological options show promise, there's little data on their cost-effectiveness for farmers. Comparisons with conventional chemical treatments in terms of expense, yield benefit, and scalability are largely absent.

6. **Need for advanced mycotoxin monitoring technologies:** Existing detection techniques are often slow, costly, and lab-dependent. Developing fast, affordable, and field-usable tools for early mycotoxin detection remains a key gap.

Future Scope

Seeds are essential for plant regeneration and form the base of nearly 90% of global food crops, so their careful production and storage is critical. Chemical fungicides used to control seed-borne fungi create hazards to human health, groundwater, biodiversity, and the atmosphere. Because of this, safer alternatives are now preferred, such as seed treatment with plant extracts, essential oils, and biopesticides. Future eco-friendly strategies for managing seed storage fungi include: Biological control: Using beneficial microbes like *Trichoderma* and *Bacillus* to suppress harmful fungi. Plant-based compounds: Essential oils and other extracts act as natural antifungal agents. Endophytic fungi: They produce bioactive metabolites that protect seeds and improve longevity. Improved storage tech: Controlled atmosphere storage and cryopreservation regulate humidity and temperature to maintain seed quality. IPM approach: Combining multiple eco-friendly methods for effective fungus management. Recent research has improved understanding of spoilage molds, mycotoxin production, early detection, dry matter losses, and interactions in stored seeds using plant-based, low-chemical options. Still, more work is needed to quantify nutritional losses in grains.

Conclusion

There is a significant variation in the diversity and severity of fungal contamination in seed samples. *Aspergillus niger* and *A. flavus* showed the highest severity rates among seed-borne fungi. Climatic issues like daily humidity, sunlight hours, precipitation, and minimum temperature significantly impacted the distribution of most seed-borne fungi.

In summary, using environmentally friendly seed treatments to manage storage fungi provides a sustainable way to support food security while minimizing ecological harm. By relying on natural compounds, biological agents, and advanced technologies, it's possible to lower dependence on synthetic chemicals and reduce their negative effects on ecosystems. With challenges like climate change, population growth, and food shortages becoming more pressing, adopting these eco-friendly methods can strengthen sustainable farming, help conserve biodiversity, and protect public health. Continued research and innovation in this area can open up new approaches to seed treatment, helping to build a more resilient and secure food system for the future.

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