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Plant-derived protectants for sustainable stored grain pest management: A review

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Abstract
Post-harvest losses caused by insect pests and microorganisms represent a major challenge to global food security, particularly in developing countries where traditional storage systems are prevalent. It is estimated that 20–30% of harvested grains are lost annually during storage due to insect infestation, microbial spoilage, and poor storage infrastructure. Traditional storage structures such as earthen bins, clay pots, bamboo containers, and underground pits play an important role in enhancing the effectiveness of botanical protectants by maintaining favorable storage conditions. The efficacy of herbal materials largely depends on factors such as grain moisture content, storage duration, environmental conditions, and the form in which botanicals are applied. Botanical protectants offer multiple advantages over synthetic pesticides, including biodegradability, reduced health risks, and minimal impact on non-target organisms. However, issues related to standardization, consistency, and large-scale application remain challenges for their widespread adoption. Overall, the integration of traditional herbal knowledge with improved storage practices provides a promising and sustainable approach for reducing post-harvest losses and ensuring long-term food security. The use of plant-derived materials and herbs for stored grain protection is a time-tested, eco-friendly alternative to synthetic pesticides. Traditional storage practices incorporate botanical materials such as neem, turmeric, garlic, sweet flag, tulsi, bay leaf, and plant oils, which exhibit insecticidal, repellent, antifeedant, antifungal, and antibacterial properties. This review synthesizes existing literature on traditional grain storage systems, herbal pest management strategies, and the modes of action of botanical protectants against stored grain pests and associated microorganisms.

Keywords: Stored grain pests, botanical pesticides, traditional grain storage, herbal protectants, post-harvest management, sustainable agriculture

Introduction

Post-harvest preservation of food grains is a critical component of agricultural sustainability and food security. Despite advancements in crop production, substantial losses continue to occur during storage due to insect pests, fungi, bacteria, and improper handling (FAO, 2011) [7]. Stored-product insects cause both quantitative losses through direct feeding and qualitative losses by contaminating grains with excreta, insect fragments, and webbing, which further promote fungal growth (Rees, 2004; Phillips & Throne, 2010) [18, 19, 24]. Major stored grain pests include *Sitophilus oryzae*, Sitophilus zeamais, Rhyzopertha dominica, *Trogoderma granarium*, *Tribolium castaneum*, and *Callosobruchus* spp., which are responsible for serious economic losses worldwide (Hagstrum & Flinn 2014) [9]. In India, storage pests alone account for nearly one-fourth of total post-harvest grain losses, severely affecting food availability and farmer income (Golob *et al*., 2002) [8]. The extensive use of synthetic insecticides following the discovery of DDT revolutionized pest management; however, their indiscriminate application has resulted in insect resistance, pesticide residues in food, environmental pollution, and adverse effects on non-target organisms (Pimentel, 2005). These concerns have renewed interest in botanical pesticides, which are biodegradable,
environmentally safe, and compatible with traditional storage systems (Isman, 2006) [12].

In recent years, increasing concerns regarding food safety, environmental pollution, and pesticide residues have encouraged the search for safer alternatives to chemical pesticides in stored grain protection. Although synthetic insecticides are effective, their continuous use has resulted in insect resistance, contamination of food grains, and adverse effects on human health and non-target organisms (Isman, 2006; Arthur, 2012) [3, 12]. Consequently, traditional grain storage practices using plant-based materials have regained attention. In many developing regions, botanical protectants such as neem (*Azadirachta indica*), turmeric (*Curcuma longa*), garlic (*Allium sativum*), tulsi (*Ocimum sanctum*), and bay leaf (*Cinnamomum tamala*) are commonly used to reduce insect infestation and microbial deterioration in stored grains (Golob *et al*., 1982; Rajendran & Sriranjini, 2008) [17, 26]. These botanicals exhibit insecticidal, repellent, antifungal, and antibacterial properties by interfering with feeding, growth, and reproduction of storage pests (Isman, 2006; Regnault-Roger *et al*., 2012) [12, 25]. In addition, botanical protectants are biodegradable, environmentally safe, and compatible with traditional storage systems, making them suitable for sustainable post-harvest pest management (Tripathi & Dubey, 2004) [31].

Stored grains are highly vulnerable to deterioration due to improper storage practices, fluctuating temperature, and high relative humidity, which together create favorable conditions for pest infestation and microbial growth. In developing countries, where traditional storage systems are still widely used, post-harvest losses remain a major challenge affecting food availability and farmer income. Smallholder farmers often lack access to modern storage technologies and rely on indigenous knowledge to preserve grains for long periods. Traditional practices involving the use of plant materials, ash, and cow dung have been developed through generations of experience and are closely linked to local agro-ecological conditions. These methods not only provide protection against storage pests but also align with sustainable agriculture principles by utilizing low-cost, locally available, and environmentally safe resources. Therefore, documenting and scientifically validating such traditional grain protection practices is essential for strengthening sustainable post-harvest management systems.

Fig 1: Grains infested by lessesr grain borer and rice weevil

Importance of Traditional Food Grain Storage Systems

Traditional grain storage systems evolved through indigenous knowledge and long-term observation of environmental conditions. These systems were designed to protect grains from biotic stresses such as insects and microorganisms, as well as abiotic factors including moisture, temperature fluctuations, and oxygen availability (Proctor, 1994; Golob *et al*., 2002) [8, 23]. Such practices emphasize natural ventilation, thermal insulation, and the use of plant-based deterrents, thereby reducing dependence on chemical pesticides. These principles align closely with modern Integrated Pest Management (IPM) strategies (Pretty & Bharucha, 2015) [22].

Traditional Structures and Techniques for Grain Storage

Aerial Storage Methods

Aerial storage involves hanging bundles of harvested grains in well-ventilated locations. This method reduces moisture accumulation and limits insect and rodent access by elevating grains above ground level (Golob *et al*., 2002) [8].

Underground Pit Storage

Underground pit storage provides a cool and stable environment that slows insect development and microbial activity. Reduced oxygen levels in sealed pits further suppress insect survival (FAO, 2011; Proctor, 1994) [7, 23].

Earthen Bins, Clay Pots, and Mud Structures

Earthen bins and clay pots are widely used due to their porous nature, which allows slow air exchange and humidity regulation. These structures reduce fungal growth and insect infestation while maintaining grain quality (Proctor, 1994) [23].

Wooden and Bamboo Containers

Wooden boxes and bamboo baskets provide adequate ventilation and durability. When combined with herbal additives such as neem leaves or sweet flag powder, these containers effectively suppress insect infestation (Golob *et al*., 2002) [8].

Fig 2: Different storage approaches

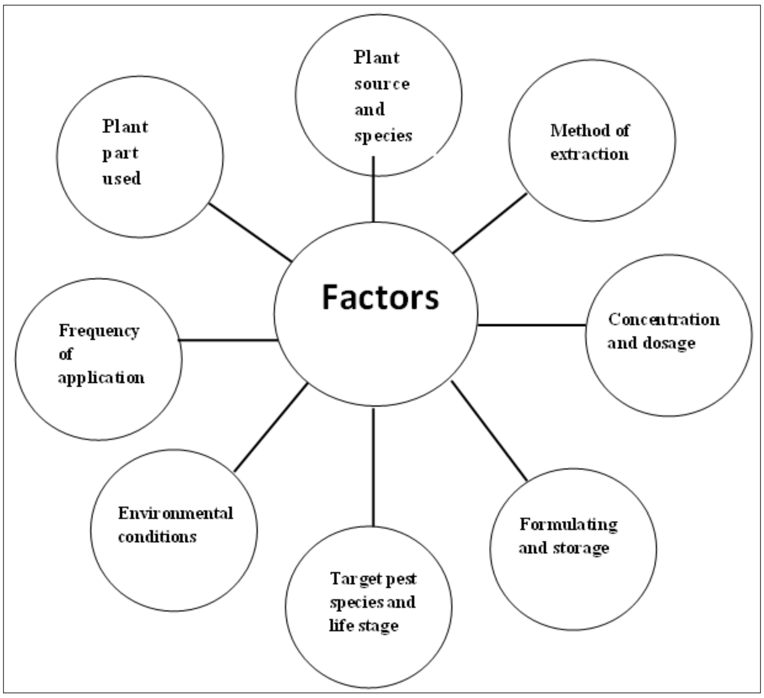

Fig 3: Factor affecting the efficacy of botanical protectants

Traditional Herbs Used in Stored Grain Protection

Traditional agricultural systems have long relied on locally available herbs and plant materials to protect stored grains from insect pests and microbial spoilage. These botanicals are applied in the form of dried leaves, powders, oils, or plant residues and act through repellent, insecticidal, antifeedant, growth-regulatory, and antimicrobial mechanisms. Their effectiveness, combined with low cost and environmental safety, makes them particularly valuable in small-scale and rural storage systems.

Neem (*Azadirachta indica*)

Neem (*Azadirachta indica*) is one of the most widely used botanical protectants in stored grain management. Neem also exhibits antifungal and antibacterial activity, thereby protecting grains from both insect damage and microbial deterioration. Neem contains bioactive compounds such as azadirachtin, salannin, and nimbin, which act as insect repellents, antifeedants, and growth regulators. Neem disrupts molting, reproduction, and feeding behavior of insects and also exhibits antifungal and antibacterial activity (Schmutterer, 1990; Isman, 2006) [12, 27].

Turmeric (*Curcuma longa*)

Turmeric (*Curcuma longa*) is commonly mixed with stored grains due to its strong antifungal and antibacterial properties. Turmeric is particularly effective in preventing mold development under traditional storage conditions. Turmeric contains curcumin, which possesses strong antifungal and antibacterial properties. Turmeric powder inhibits microbial growth and reduces grain spoilage during storage (Dubey *et al*., 2010) [6].

Garlic (*Allium sativum*)

Garlic (*Allium sativum*) is used either as crushed cloves or powder in grain storage. Sulfur-containing compounds released from garlic is allicilin, act as insect repellents and suppress fungal and bacterial growth. Garlic interferes with insect metabolic processes and reduces infestation levels when used regularly. (Ankri & Mirelman, 1999) [2].

Sweet Flag (*Acorus calamus*)

Sweet flag (*Acorus calamus*) rhizome powder is traditionally added to stored grains for its strong insecticidal properties.Sweet flag rhizomes contain the bioactive compounds α-asarone and β-asarone, which affect the insect nervous system, causing paralysis and mortality. It is highly effective against coleopteran stored grain pests (Tripathi *et al*., 2002) [30].

Tulsi (*Ocimum sanctum*)

Tulsi (*Ocimum sanctum*) leaves emit essential oils rich in eugenol and methyl eugenol, which act as fumigants and repellents. These oils disrupt insect feeding behavior and microbial cell membranes (Koul *et al*., 2008) [14]. Tulsi is often used in combination with other herbs to enhance storage protection.

Bay Leaf (*Cinnamomum tamala*)

Bay leaf is commonly placed in storage structures because of its strong aroma and bioactive constituents. It release aromatic volatile compounds that reduce oviposition and act as mild insecticidal and antifungal agents.which help in limiting pest population buildup and microbial contamination (Regnault-Roger *et al*., 2012) [25]. The volatile oils released from bay leaves act as repellents, discouraging insect entry and reducing egg laying by stored grain pests.Its use is particularly effective when combined with other botanicals such as neem or tulsi. Due to its easy availability and safety, bay leaf remains a popular and effective traditional protectant in household and small-scale grain storage systems.

Ash and cow dung

Wood ash has traditionally been mixed with stored grains to control insect pests by creating an abrasive layer that damages the insect cuticle, leading to dehydration and mortality. It also fills grain interspaces, restricting insect movement and oviposition. Dried cow dung, commonly used in rural storage structures, acts as a natural repellent and antimicrobial agent due to the presence of bioactive compounds and beneficial microbes. When applied to storage bins or walls, cow dung helps reduce insect entry and suppress microbial growth, thereby enhancing grain preservation.

Fig 4: Herbs used in grains

Table 1: Plant parts used in stored-grain protection and their functional roles

Plant part	Botanical examples	Target organism	Functional role	References
Leaves	Neem, Tulsi, Bay leaf	Insects, fungi	Repellent and antimicrobial activity	Isman (2006) [12]; Regnault-Roger *et al*. (2012) [25]
Seeds	Neem seed kernel	Insect pests	Growth inhibition and antifeedant effect	Schmutterer (1990) [27]; Isman (2019) [13]
Rhizomes	Turmeric	Fungi, bacteria	Antifungal and antibacterial action	Prasad & Naik 2003 [21]; Tripathi & Dubey (2004) [31]
Bulbs	Garlic	Insects, bacteria	Toxicity and cell wall disruption	Cowan (1999) [5]; Upadhyay & Singh (2012) [32]
Bark	Cinnamon	Insects, fungi	Oviposition deterrent and antimicrobial activity	Hammer *et al*. (1999) [10]; Nerio *et al*. (2010) [15]

Management of Microorganisms in Stored Grains

Insect Management

Insect infestation is a major cause of quantitative and qualitative losses in stored grains, leading to reduced weight, nutritional value, and market quality. Several studies have reported that botanical protectants such as neem, garlic, turmeric, tulsi, and bay leaf are effective against stored-grain insects due to their repellent, antifeedant, ovicidal, and growth-regulating properties (Isman, 2006) [12]. Plant-based materials interfere with insect feeding behavior and reproductive potential, thereby suppressing pest population buildup during storage (Rajendran & Sriranjini, 2008) [26]. Neem-derived products, in particular, have shown strong toxicity and repellency against major stored-grain pests such as *Sitophilus spp.* and *Rhyzopertha dominica* (Tripathi *et al*., 2002) [30]. Essential oils and plant extracts also act on insect nervous and hormonal systems, reducing survival and development (Regnault-Roger *et al*., 2012) [25]. Compared to synthetic insecticides, botanical methods are biodegradable, environmentally safe, and less likely to induce resistance, making them suitable for sustainable stored-grain pest management.

Fungal Management

Fungal infestation in stored grains leads to spoilage, discoloration, and mycotoxin contamination. Traditional practices such as sun drying and low-moisture storage inhibit fungal growth. Traditional sun drying, neem leaves, turmeric powder, and clay containers reduce grain moisture and inhibit mold growth and mycotoxin production (Magan & Aldred, 2007; Pitt & Hocking, 2009) [20]. Thus, herbal treatments combined with proper storage conditions help maintain grain quality and safety.

Bacterial Control

Bacterial contamination in stored grains reduces quality and accelerates spoilage under humid conditions. Proper drying and hygienic storage practices limit bacterial survival and multiplication. Therefore, herbal treatments along with clean storage conditions help preserve grain quality Botanicals such as garlic, turmeric, and tulsi suppress bacterial contamination by disrupting cell walls and metabolic pathways (Ankri & Mirelman, 1999; Dubey *et al*., 2010) [2, 6].

Nematode Suppression

Nematodes are mainly field pests but may survive in stored grains under high moisture conditions. Traditional practices such as sun drying and low moisture storage suppress nematode survival (FAO, 2011) [7]. Neem (*Azadirachta indica*) possesses nematicidal properties that inhibit nematode feeding and reproduction (Schmutterer, 1990) [27]. Thus, botanical treatments combined with hygienic storage effectively prevent nematode persistence (Golob *et al*., 2002) [8].

Viral Management

Viruses do not directly damage stored grains but may spread through insect vectors. Stored-grain insects can act as mechanical carriers of plant viruses (Phillips & Throne, 2010) [18, 19]. Botanicals like neem and essential oils reduce insect vectors by repellent action (Shaaya *et al*., 1997; Isman, 2006) [12, 28]. Hence, botanical pest management indirectly helps in viral disease prevention (Regnault-Roger *et al*., 2012) [25].

Table 2: Target-specific action of botanical protectants in stored-grain management

Target organism	Botanical materials used	Mode of action	Effect on stored grains	References
Insect pests	Neem, Tulsi, Bay leaf	Repellent, antifeedant, growth inhibition	Reduced infestation and grain damage	Isman (2006) [12]; Singh & Srivastava (2015) [29]
Fungi	Turmeric, Garlic, Neem	Inhibition of spore germination	Reduced mold growth and mycotoxin risk	Prasad and Naik 2003 [21]; Tripathi & Dubey (2004) [31]
Bacteria	Garlic, Tulsi, Clove	Cell wall disruption and enzyme inhibition	Improved grain hygiene and safety	Cowan (1999) [5]; Hammer *et al*. (1999) [10]
Nematodes	Neem seed powder	Reduced mobility and feeding activity	Lower nematode survival	Chitwood (2002); Akhtar & Malik (2000) [1, 4]
Storage mites	Neem leaves, aromatic herbs	Repellency and behavioral avoidance	Reduced contamination and allergen risk	Isman (2020); Regnault-Roger *et al*. (2012) [25]

Future Prospects of Botanical-Based Stored Grain Protection

The increasing demand for safe and sustainable food storage practices has renewed global interest in botanical pest management. Plant-based protectants offer multiple advantages, including biodegradability, low toxicity to humans and non-target organisms, reduced risk of resistance development, and compatibility with traditional storage systems. Advances in extraction techniques, formulation science, and nano-based delivery systems have further enhanced the efficacy and stability of botanical products.

Future research should focus on standardizing dosages, improving shelf life, and developing user-friendly formulations suitable for large-scale application. Integration of botanical protectants with modern storage technologies, hermetic storage systems, and Integrated Pest Management (IPM) frameworks can significantly reduce post-harvest losses. Policy support, farmer awareness programs, and commercialization of validated herbal formulations will be critical for wider adoption. Scientific validation of indigenous knowledge through multidisciplinary research can bridge the gap between traditional practices and modern storage requirements.

Conclusion

Stored grain protection is a critical component of food security, particularly in developing countries where post-harvest losses remain high. Traditional herbal practices and botanical materials provide an effective, economical, and environmentally sustainable alternative to synthetic pesticides. Botanicals such as neem, turmeric, garlic, sweet flag, tulsi, and bay leaf exhibit diverse modes of action, including insecticidal, repellent, antifeedant, antifungal, antibacterial, and growth-regulatory effects.

The integration of traditional storage structures with herbal pest management practices enhances grain preservation while minimizing health and environmental risks. Although challenges such as standardization and large-scale adoption persist, continued research and technological advancements offer promising opportunities. Harnessing indigenous knowledge alongside modern scientific innovations can play a vital role in reducing post-harvest losses and ensuring long-term food security.

Stored grain protection is a critical component of food security, particularly in developing countries where post-harvest losses remain high. Traditional herbal practices offer an effective, economical, and environmentally sustainable alternative to synthetic pesticides. Botanical materials such as neem, turmeric, garlic, sweet flag, tulsi, and bay leaf exhibit diverse modes of action including insecticidal, repellent, antifeedant, antifungal, antibacterial, and growth-regulatory effects, making them suitable for integrated stored-grain pest management.

The integration of traditional storage structures with herbal pest management practices enhances grain preservation while minimizing health and environmental risks associated with chemical pesticides. Although challenges such as variability in efficacy, lack of standardization, and limited large-scale validation exist, continued research and technological advancements can help overcome these limitations. Scientific validation of indigenous knowledge, development of standardized formulations, and adoption of botanicals within integrated pest management (IPM) frameworks can significantly reduce post-harvest losses.

Furthermore, promoting farmer awareness and policy support for plant-based grain protection strategies can contribute to sustainable agriculture and long-term food security. The synergistic use of traditional knowledge alongside modern scientific innovations holds great promise in ensuring safe, eco-friendly, and resilient stored-grain management systems for the future.

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Conflicts of Interest

The authors declare no conflicts of interest.

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