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A comprehensive review on advances in storage-pest management in seed spices

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Abstract

Seed spices constitute an important component of global agriculture due to their multifaceted use in culinary, pharmaceutical, nutraceutical and industrial sectors. However, prolonged storage makes them highly vulnerable to pests, causing 5-7 per cent post-harvest losses, rising up to 58 per cent under severe infestation. Major pests like *Lasioderma serricorne*, *Stegobium paniceum*, *Oryzaephilus surinamensis* and *Tribolium castaneum* significantly reduce seed quality and market value. Among storage pests, cigarette beetle (*Lasioderma serricorne*) is highly destructive and polyphagous, completing its life cycle within 60-90 days and causing severe internal seed damage. Besides insects, fungi, mites and rodents accelerate deterioration and mycotoxin risks. Advanced detection tools, including sensors, imaging and artificial intelligence are vital for timely management. Management of storage pests in seed spices requires an integrated strategy combining preventive, chemical, physical and botanical approaches. Proper drying, sanitation, hermetic storage and MAP (modified atmosphere packaging) are essential preventive measures. Besides phosphine, alternative fumigants and residue-free technologies like CO₂, ozone and FHAT (forced hot air treatment) provide sustainable pest management solutions. Botanical pesticides and seed spice-derived essential oils offer eco-friendly alternatives for storage pest management, while nano emulsion technology enhances their stability and efficacy. Integrating botanicals, advanced detection, and Integrated Pest Management can reduce losses and preserve seed quality sustainably. This review highlights the biology, infestation mechanisms, detection tools, and integrated management strategies for storage pests of seed spices. The information is crucial for reducing post-harvest losses, preserving seed quality, ensuring food safety and maintaining the economic and export value of seed spices in the future.

Keywords: Seed spices, storage pests, cumin, coriander, fennel, post-harvest losses, fumigation, hermetic storage, integrated pest management.

Introduction

Seed spices occupy a unique and economically significant position in global agriculture due to their indispensable role in culinary, pharmaceutical, nutraceutical and industrial sectors. Unlike many agricultural commodities, seed spices are valued not only for their flavoring properties but also for their rich composition of essential oils, volatile aromatic compounds and diverse bioactive metabolites that impart medicinal and preservative properties. Major seed spices such as cumin (*Cuminum cyminum* L.), coriander (*Coriandrum sativum* L.), fennel (*Foeniculum vulgare* Mill.), fenugreek (*Trigonella foenum-graecum* L.), ajwain (*Trachyspermum ammi* L.), dill (*Anethum graveolens* L.), caraway (*Carum carvi* L.), anise (*Pimpinella anisum* L.), and nigella (*Nigella sativa* L.) form an integral part of the spice economy, particularly in India, which is recognized as one of the world's largest producers, consumers, and exporters of seed spices.

Owing to their seasonal production and continuous market demand, these commodities are often stored for extended periods before processing, marketing, export or use as planting material. However, this prolonged storage creates favourable conditions for the infestation and multiplication of storage pests, making post-harvest protection a critical challenge. Seed spices, because of their high oil content and aromatic nature, are particularly vulnerable to insect pests, mites and rodents, which can cause both quantitative and qualitative deterioration. Post-harvest losses in seed spices have been estimated at 5-7 per cent (ICAR-CIPHET, 2015), with insect pests alone contributing nearly 2.55 per cent of these losses (Krishnamurthy, 1975). Under severe storage conditions, losses may escalate up to 58.02 per cent, depending upon the crop, storage period, and environmental factors (Kant *et al.*, 2013). The magnitude of this problem is further emphasized by global estimates indicating that insect pests account for nearly 10–20 per cent of total storage losses in agricultural commodities (Esther *et al.*, 2014). Rajendran and Sriranjini (2008) reported that over 600 species of beetles, 70 species of moths and 355 species of mites are associated with stored-product deterioration worldwide but in seed spices, storage pests are only limited to few numbers (Table 1). In seed spices, these pests cause direct feeding damage, resulting in weight loss, depletion of food reserves,

reduced seed viability, poor germination and weakened seedling vigor. More importantly, infestation degrades essential oil composition and volatile aromatic compounds, leading to a decline in flavor, fragrance and medicinal quality. Pest contamination through insect fragments, excreta, webbing and dead insects further reduces market acceptability, especially in premium and export-oriented markets.

In addition to primary damage, insect metabolic activity increases temperature and moisture within storage systems, creating microenvironments conducive to fungal growth and secondary microbial infestations. This not only accelerates seed deterioration but also increases the risk of mycotoxin contamination, posing serious food safety concerns. Given the strict phytosanitary and quality standards in international trade, even minor pest infestations can result in consignment rejection, economic penalties, and reputational losses. Therefore, effective storage pest management is not merely a protective measure but an essential strategy for safeguarding the quality, viability, shelf life and economic value of seed spices. In this context, developing sustainable storage technologies and integrated pest management (IPM) approaches has become imperative to minimize post-harvest losses and ensure the long-term profitability of the seed spice industry.

Mode of storage pest infestation

Infestation of stored commodities often begins in the field, where storage-associated insect species attack crops during maturation and ripening. These early infestations may remain undetected and continue into post-harvest systems, where favourable storage conditions promote their survival and multiplication (Sallam, 1999; Hagstrum and Phillips, 2017). In addition to field carryover, storage environments themselves serve as important sources of reinfestation. Insects persisting in cracks, crevices, old storage bags and previously used containers can easily infest newly stored produce, while cross-contamination among storage lots further aggravates the problem (Perez-Mendoza *et al.*, 2004). Agricultural machinery such as harvesters and threshers also contribute to pest transfer (Sinclair and White, 1980). Furthermore, the movement of infested commodities through trade and transportation, along with active flight of strong-flying insect species, facilitates their rapid dissemination across storage systems (Ridley *et al.*, 2011).

Table 1: Major Storage Insect Pests of Seed Spices

S.N.	Name of Storage pests	Seed Spices	Damage symptoms
1.	Cigarette Beetle (<i>Lasioderma serricorne</i>)	Cumin, Coriander, Fennel & Ajwain	Hollowing of seeds and making the seed into powdery
2.	<i>Stegobium paniceum</i>	Seed spices	Boring and powdering
3.	<i>Tribolium castaneum</i>	Spice powders	External feeding
4.	<i>Oryzaephilus surinamensis</i>	Stored seeds	Surface feeding
5.	<i>Trogoderma granarium</i>	Seed spices	Severe feeding and contamination
6.	<i>Corcyra cephalonica</i>	Stored seeds	Webbing
7.	<i>Cadra cautella</i>	Processed spices	Webbing and contamination
8.	<i>Plodia interpunctella</i>	Packaged spices	Feeding and contamination

Types of stored pests

Stored-product insect pests can be classified based on damage severity, feeding behaviour, and ecological association. According to their feeding habits, they are broadly categorized into primary, secondary, and mould-indicating pests (Srivastava and Subramanian, 2016).

In the absence of proper fumigation and storage management, pest's damage may range from 10-30 per cent, causing significant quantitative and qualitative losses.

Primary stored pests: Primary pests attack on intact and healthy seeds by penetrating the seed coat and feeding internally, making them highly destructive. Major examples include weevils (*Sitophilus* spp.), lesser grain borer (*Rhyzopertha dominica*), and Angoumois grain moth (*Sitotroga cerealella*).

Secondary stored pests: Secondary pests infest broken, damaged or processed grains, often following primary infestation; flour beetles (*Tribolium* spp.) are common examples.

Mould indicating pests: Mould-indicating pests are associated with fungal growth under high-moisture conditions and indicate poor storage hygiene. Important examples include black fungus beetle (*Alphitobius diaperinus*) and foreign grain beetle (*Ahasverus advena*), which signify advanced deterioration.

Major storage insect-pests infesting seed spices

Cigarette Beetle (*Lasioderma serricorne*)

The cigarette beetle, *Lasioderma serricorne* (F.) (Coleoptera: Anobiidae), is an important pest of seed spices including the food and tobacco industry in many regions of the world (Edde, PA, 2019). It lives in dark or

poorly lit areas and also seen in cracks, corners and crevices. The beetles can become active in bright, open areas, but are most active at dusk and over night. *L. serricorne* causes damage to a variety of stored products. They feed on cereal, dates, dried fish, ginger, grain, pepper, pharmaceuticals, raisins and seed spices.

Life cycle

This beetle, undergoes complete metamorphosis (holometabolous development) comprising four distinct stages: egg, larva, pupa and adult. The duration of the life cycle varies considerably depending on temperature, relative humidity, and food quality, but it is generally completed within 40-50 days under favorable storage conditions (Mahroof and Phillips, 2008). Among 19 different spices studies Cayenne pepper (*Capsicum annum* L. var. *glabriusculum*) and paprika (*C. annum* L.) were the most favorable diets for the development of *L. serricorne* (LeCato, 1978), whereas, coriander seeds (*Coriander sativum* L.) were the most suitable host for oviposition (Dimetry *et al.*, 2004). Adult females lay approximately 10-100 eggs either singly or in clusters on the surface of stored commodities or within crevices of storage structures. The eggs are oval, translucent white, and measure about 0.5 mm in length. Egg incubation generally lasts for 5-10 days, after which larvae emerge and begin feeding on the stored material. The larval stage is the most destructive phase of the life cycle. Newly emerged larvae are creamy white, C-shaped and covered with fine hairs. Larvae actively feed on seed tissues, spice powders, and other stored products, causing extensive quantitative and qualitative losses. Depending on environmental conditions, the larval stage may consist

of 4-6 instars and lasts for approximately 20-50 days. During this period, larvae tunnel into seeds and produce characteristic powdery residues (Figure 1). Upon completion of larval development, the mature larva constructs a pupal chamber using food particles and frass. Pupation occurs within this protective cocoon and lasts for approximately 7-18 days. The pupa is initially creamy white and gradually darkens before adult emergence. Newly emerged adults are light brown and become reddish-brown with age. Adults are strong fliers and are responsible for dispersal and colonization of new storage facilities. Although adults feed very little, their primary role is reproduction. Adult longevity generally ranges from 2-6 weeks depending on environmental conditions. Under optimum conditions of 28-35°C temperature and 65-75% relative humidity, several overlapping generations may occur annually, leading to rapid population build-up and severe infestations in stored seed spices.

Host Range: *L. serricorne* is a highly polyphagous storage pest capable of infesting a wide range of stored agricultural commodities. Among seed spices, it is commonly associated with cumin (*Cuminum cyminum* L.), coriander (*Coriandrum sativum* L.), fennel (*Foeniculum vulgare* Mill.), and ajwain (*Trachyspermum ammi* L.). In addition to whole seed spices, the pest readily infests processed spice products such as paprika, chili powder, turmeric powder, and various spice blends.

Damage Symptoms:

Larvae feed internally on stored seeds, consuming the endosperm and other nutritive tissues. Infestation results in hollowing of seeds, accumulation of powdery frass, reduction in seed weight, deterioration of essential oil content and aroma, and significant loss of seed viability and germination capacity. Severe infestations may also contaminate the commodity with insect fragments and excreta, thereby reducing its market and export quality.

Storage pest detection in godown

Physical Detection Methods: Physical detection methods are the most basic and widely used techniques for identifying insect infestation in stored grains. The most cases of insect infestation come from field, and another source is the store house. The insect infestation generally remains undetected until adults

are seen. By the time these adults are detected, much of seeds are already damaged. Storage pests in store are common for fennel, coriander, cumin, ajwain, etc. Excess moisture and mould are mainly responsible for the deterioration in quality of stored materials. Insect and mite infestation in stored seed spices occurs at temperature ranging between 3 and 30°C and above 12% moisture content in stored seeds (Kant *et al.*, 2013).

Mechanical and Chemical Detection Methods:

Mechanical and chemical approaches help in identifying internal infestations and estimating insect density more accurately. Techniques such as Berlese funnel extraction, uric acid estimation, and electrical conductance measurements are commonly used for this purpose. These methods provide better precision than visual inspection and are particularly useful in assessing concealed insect damage within grain kernels.

Sensor-Based Detection Methods:

Sensor-based detection systems utilize biological, acoustic, and volatile signals generated by insects for early infestation diagnosis. Technologies such as acoustic sensors, biosensors, and electronic noses (E-Nose) can detect insect movement, feeding activity, and pest-induced volatile compounds without damaging the grains. These methods offer rapid, non-invasive, and highly sensitive detection, making them suitable for modern storage systems.

Spectral and Imaging Detection Methods:

Spectral and imaging techniques use advanced optical and electromagnetic technologies to identify insect presence and grain damage. Methods like RGB imaging, thermal imaging, X-ray imaging, and near-infrared spectroscopy (NIRS) can detect both external and internal infestations with high accuracy (Ageh *et al.*, 2025; Brezolin *et al.*, 2018). These approaches are fast, non-destructive, and effective for large-scale grain quality assessment.

Artificial Intelligence and Deep Learning:

Artificial intelligence based detection methods have revolutionized stored grain insect monitoring by enabling automated and accurate pest identification through computer vision systems. These approaches use advanced deep learning algorithms such as Convolutional Neural Networks (CNN) for feature

extraction, Region-based Convolutional Neural Networks (R-CNN) for object localization and classification, and You Only Look Once (YOLO) models for real-time insect detection (Bochkovskiy *et al.*, 2020).

Other stored grain pests in seed spices

Storage fungi in seed spices & their control measures

Storage fungi are an important cause of deterioration in stored grains and food commodities, leading to quality loss and reduced seed viability. These fungi are broadly classified into field fungi and storage fungi, although the distinction is often unclear as fungal infection may begin in the field and continue during storage. The primary source of fungal contamination is usually the field, while storage conditions determine further growth and spread. Important storage fungi

mainly belong to the genera *Aspergillus*, *Fusarium*, and *Penicillium*, which develop under favorable moisture and temperature conditions. Their growth is influenced by nutrient composition of grains, storage humidity, temperature, and biotic factors such as insect infestation. Storage fungi are more common in insect-infested lots because insects increase moisture levels and facilitate the spread of fungal spores. Different fungal species require specific minimum grain moisture levels for development, ranging from 13.5% in *Aspergillus restrictus* to 18–19% in *Fusarium* spp. Fungal development is promoted when grains are inadequately dried before storage, physically damaged during harvesting or handling, or when moisture content rises during storage, emphasizing the importance of proper drying and storage management.

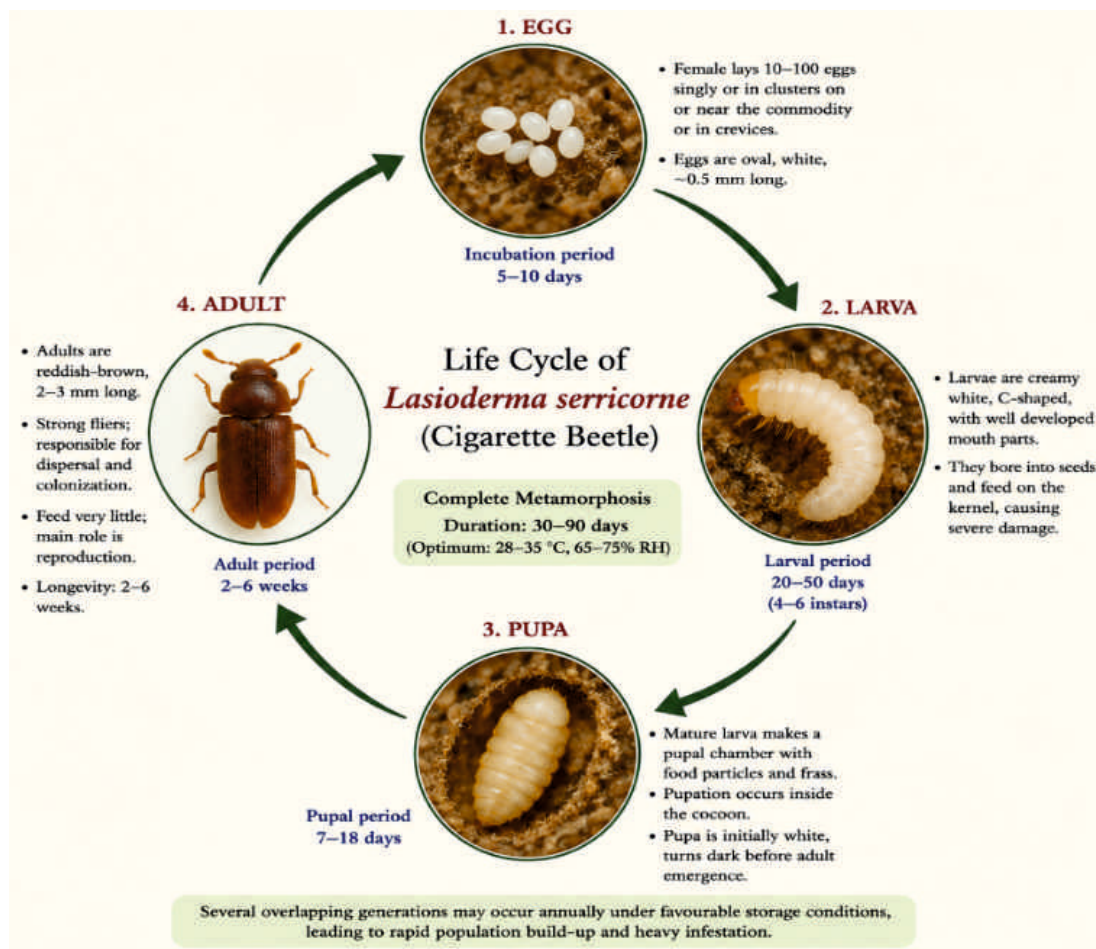
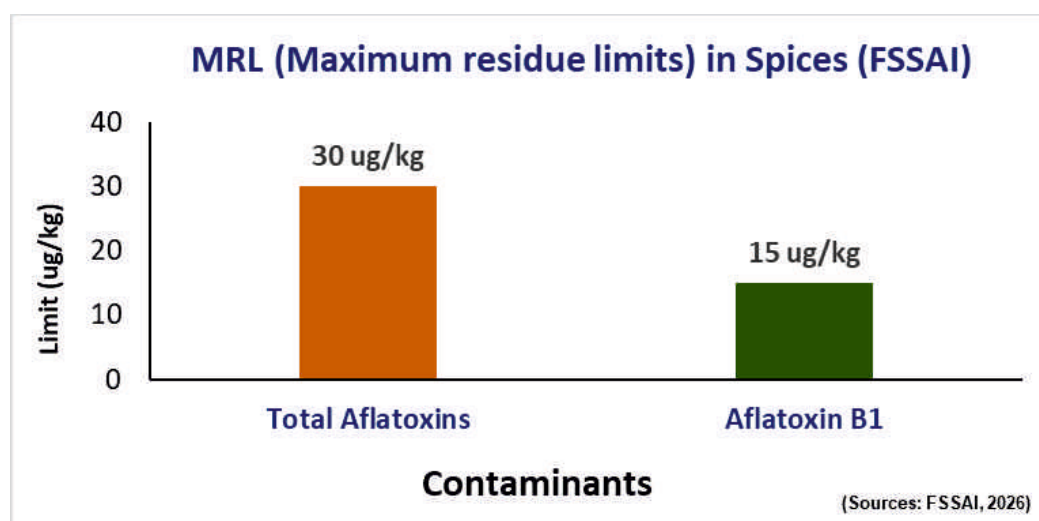


Fig. 1: Life cycle of cigarette beetle (*Lasioderma serricorne*)

Table 4: Different storage fungi in agriculture and their affected commodities including seed spices

Fungus species	Common commodities affected	Seed spices affected
<i>Alternaria alternata</i>	Rice, sorghum, soybeans	Coriander, fennel, cumin
<i>Alternaria longissima</i>	Rice, sorghum	Coriander, fenugreek
<i>Alternaria padwickii</i>	Rice	Dill, fennel
<i>Aspergillus flavus</i>	Maize, groundnuts, sorghum, soybeans	Mostly seed spices
<i>Fusarium moniliforme</i>	Maize, sorghum, soybeans	Coriander, cumin, fennel
<i>Fusarium semitectum</i>	Maize	Fenugreek, dill
<i>Penicillium citrinum</i>	Sorghum, soybeans	Cumin, ajwain, coriander
<i>Aspergillus niger</i>	Cereals, oilseeds	Cumin, fennel, black cumin
<i>Rhizopus stolonifer</i>	Stored grains, pulses	Coriander, fenugreek
<i>Cladosporium spp.</i>	Cereals, legumes	Dill, fennel, coriander

Source: Gwinner *et al.*, 1990**Fig 6:** MRL of mycotoxins in spices or spices mix food items

Storage Mites Associated with Seed Spices & their control measures

Storage mites are important secondary pests of stored seed spices, particularly under conditions of high moisture and relative humidity. The most commonly reported species include *Acarus siro* (grain mite), *Tyrophagus putrescentiae* (mold mite), and *Lepidoglyphus destructor* (storage mite). These mites feed on damaged seeds, fungal growth, and organic debris, resulting in deterioration of seed quality and marketability. Infestation is characterized by the development of a musty odor, discoloration of seeds, reduced germination, and contamination of produce. Management of storage mites primarily depends on

preventive strategies aimed at minimizing favorable conditions for their development. These include drying seeds to safe moisture levels (<8-10%), maintaining relative humidity below 65%, ensuring strict sanitation of storage structures, and using moisture-proof or hermetic storage containers to restrict mite proliferation. The efficacy of fumigation treatments against storage mites is generally assessed by recording mortality of adults and nymphs based on the absence of movement following physical stimulation after a two-day recovery period, while egg mortality is confirmed by the failure of hatching within four days after fumigation.

Rodent infestation in stored seed spices & their

control measures

Rodents are among the most destructive vertebrate pests in stored agricultural commodities and contribute significantly to post-harvest losses in seed spices through both direct consumption and indirect contamination. The major rodent species commonly associated with storage structures include the house mouse (*Mus musculus*), black rat (*Rattus rattus*), and Norway rat (*Rattus norvegicus*). Besides consuming stored seeds, rodents contaminate commodities with urine, feces, hair, and nesting materials, making them unsuitable for consumption and reducing market value. They also damage storage structures, packaging materials, and electrical systems and act as vectors of several pathogens, thereby posing food safety and public health risks. Effective rodent management in seed spice storage requires an integrated approach involving sanitation, exclusion, trapping, repellents, and chemical control. Maintaining hygienic storage conditions, eliminating food residues, and removing nesting sites are essential preventive measures. Rodent-proofing through sealed openings, wire mesh barriers, and tight-fitting doors significantly reduces infestation. Rodent repellents, including sodium alginate-based microcapsules containing 5 per cent CA, have shown effective and economical results under storage conditions, while formulations based on methyl anthranilate mixed with essential oils have also demonstrated good repellent activity (Bala and Babbar, 2019). Chemical management mainly relies on poison baiting using acute rodenticides such as *zinc phosphide* and anticoagulants such as *bromadiolone*. A 2 per cent zinc phosphide bait prepared with 935 g cereal bait, 20 mL edible oil, 20 g sugar, and 25 g zinc phosphide is recommended for outdoor storage, whereas 0.005 per cent bromadiolone bait containing 940 g bait, 20 mL oil, 20 g sugar and 20 g bromadiolone is preferred for indoor storage (Singla *et al.*, 2021). Additionally, aluminium phosphide fumigation remains an effective option for severe rodent infestations by releasing toxic phosphine gas under airtight conditions.

Assessment of post -harvest loss occurred by storage pest

Assessment of storage losses is complex due to methodological limitations and the need for skilled personnel. Most evaluations are conducted on a small

experimental scale and extrapolated to bulk storage conditions, which may not always reflect actual losses. Accurate identification of insect infestation is the first and most critical step, as the type and severity of damage vary among species. Early diagnosis helps prevent rapid pest multiplication and enables timely implementation of effective storage management practices. Although numerous insect species are associated with stored commodities, only a few are considered major pests because of their high destructive and economic impact.

Management of stored grain pests

Precautionary management of stored pests in seed spices

Pre-storage Phase: The pre-storage phase is a critical stage in minimizing pest infestation in seed spices, as it determines the initial quality of the stored produce.

The harvested seeds should be thoroughly cleaned to remove dust, debris, and previously infested materials that may act as sources of contamination.

Proper drying to safe moisture levels is essential to prevent insect multiplication and fungal development. Sun drying is the most common method adopted to dry the produce, but driers are more efficient since they dry the produce within a shorter period and more efficiently and are useful during inclement weather.

The use of scientifically designed storage structures such as metal bins, silos, and hermetic containers provides effective barriers against insects, rodents, and moisture.

Modified Atmosphere Packaging (MAP) is an effective non-chemical storage technology used to manage insect pests in seed spices by altering the gaseous composition under hermetic storage conditions.

Packaging materials: The use of safe and pest-resistant packaging materials further ensures protection against moisture ingress and insect invasion before storage. Storage in jute bags lined with alkathene film also affords sufficient protection which can be rendered more effective by impregnating the bags with a suitable insecticide. Storage in bags of low-density poly ethylene and aluminium foil laminated with low-density poly ethylene also affords protection against storage pests. Recently, some hermetic bags viz., Purdue Improved Crop Storage bag (PICS™) (Two high density polyethylene liners with 80 µm thickness),

GrainPro hermetic bag (GPB™) (Single multilayer polyethylene liner with 78 µm thickness), Save Grains bag (SGB®) (Single multilayer polyethylene liner EVOH inside Japanese technology with 80 µm thickness) and Ecotect hermetic bags (EHB®) were used to extend the storability of green gram seed against *Callosobruchus chinensis* (Yewle *et al.*, 2022).

Building structure: The building or structure for storage should be compact and weather proof with tight fitting doors. Wooden structures are to be treated suitably to resist insect attack. Concrete and metal structures, though expensive, are ideal on a long-term basis. Store cleanliness involves sweeping, removal and destruction of produce residues, spillage and wastes. Careful inspection and cleaning of nooks and crevices where many storage insects generally hide and lay eggs are also important.

Storage Phase: During the storage period, maintaining optimum environmental and physical conditions is essential for protecting seed spices from insect pests. In addition, regulating storage temperature and humidity helps slow insect development, while regular monitoring of seed lots allows early detection of infestation and timely corrective measures.

Post-storage phase: The post-storage phase focuses on preserving seed quality and preventing secondary infestation during handling, transportation, and utilization. Periodic inspection of stored seed lots is necessary to identify signs of damage such as discoloration, powdering, and insect presence. Quality assessment through germination, moisture, and purity testing ensures that the seeds remain viable and suitable for planting or marketing. Advanced pest detection techniques can also be employed to detect hidden infestations before distribution. Proper handling practices during unloading, transport, and processing are equally important to avoid mechanical injury and re-infestation of the stored seed spices.

Chemical management of stored pests in seed spices

Chemical control has been one of the most widely practiced strategies for managing storage insect pests in seed spices due to its rapid action, high efficacy, and suitability for large-scale storage systems. These methods involve both preventive and curative

approaches to protect stored produce from infestation and maintain quality during prolonged storage.

Pre-storage Sanitation and Surface Treatment

Proper sanitation of storage structures is the first step in chemical pest management. Before storage, warehouses, godowns, bins, and containers should be thoroughly cleaned to remove dust, debris, and residual infested material, which often act as sources of reinfestation. After cleaning, contact insecticides are sprayed on walls, floors, roofs, and storage surfaces to eliminate hidden insect populations. In some cases, the outer surfaces of bagged commodities are also sprayed. However, care must be taken to avoid direct contamination and pesticide residue in seed spices intended for human consumption or export.

Fumigation: A Curative Chemical Approach

Fumigation is considered one of the most effective methods for controlling storage pests because fumigant gases penetrate deep into stored commodities and destroy insects at all life stages, including eggs, larvae, pupae, and adults. The treatment is carried out in airtight enclosures for a specific exposure period, followed by proper aeration for at least 72 hours to ensure safety. Due to its broad-spectrum activity, fumigation is widely used in commercial storage systems. Earlier studies demonstrated that impregnation of jute bags lined with alkathene (500 gauge) using malathion (0.2%) significantly reduced pest infestation during storage (Abraham, 1975). Similarly, fumigation with methyl bromide for six hours was found effective in disinfesting stored produce. Aluminium phosphide is now the most commonly used fumigant in seed spice storage, applied at the rate of 3 tablets per metric tonne of produce or 21 tablets per 28 m³ of storage space, with an exposure period of 2–3 days under airtight conditions (Jacob, 1986).

Silo Fumigation: In silo fumigation, fumigants are directly introduced into the commodity bulk, where they react with internal moisture and are circulated using systems such as the J-system for uniform gas distribution. This method is highly effective for large-scale bulk storage.

Modified Breathing Respirator (MBR) System: The MBR safety system is designed to protect fumigation operators from exposure to toxic gases by ensuring

controlled breathing conditions during treatment. This technology enhances worker safety during enclosed-space fumigation (Anonymous (2026)).

Phosphine Generator Technology: Phosphine generators provide controlled release of phosphine gas through a chemical reaction, ensuring uniform distribution, deep penetration, and faster action. This technology improves fumigation efficiency and enhances pest control in large storage facilities).

Stack Fumigation: Stack fumigation is widely practiced in warehouses and godowns where commodities are stored in stacked bags. The stacks are covered with gas-proof sheets and fumigated with approved fumigants. This method ensures effective control of pests at all life stages, prevents reinfestation, and helps maintain product quality, hygiene, and compliance with export standards.

Commodity Fumigation: Commodity fumigation is an effective pest control treatment used to protect stored and transported goods such as grains, pulses, spices, wooden pallets, textiles, and other commodities from insect infestations. Commodity fumigation helps maintain product quality, prevents economic losses, and ensures compliance with storage and export requirements.

Inspection of the cargo and storage conditions, for any sign of storage pest infestation

Selection of suitable fumigants based on the type of commodity and target pests.

Application of fumigants by using specialized equipment to ensure complete penetration and elimination of pests at all life stages.

Container Fumigation: Container fumigation is a specialized process aimed at eradicating pests from shipping containers used to transport goods. Pests can easily deposit away on cargo and pose a threat to the reliability of the shipment. Fumigation ensures that containers are pest-free, thereby protecting the goods inside from damage and contamination.

Full container load Fumigation: FCL containers involve treatment of shipping container packed with goods destined for export. Container fumigation is process designed as per international standard by IPPC & national quarantine regulation of importing countries.

Loose Container Load (LCL) Fumigation: LCL containers involve treating individual items separately and loaded in container. This fumigation ensures control of pest from each item and maintaining overall shipment pest free



Stake fumigation



Export Container Fumigation

Source: (<https://www.sevafacility.com/stack-fumigation.html>)

Fig 2: different types of storage fumigation methods Images



Fig. 3. Experimental setup for CO₂ fumigation to control wheat storage pest *R. dominica* (Kumar *et al.*, 2022)

International and National Phytosanitary Standards Governing Fumigation Practices

The safe international movement of agricultural commodities and plant-based materials requires strict adherence to phytosanitary regulations to prevent the transboundary spread of invasive pests and diseases. To address this challenge, a structured regulatory framework has been established at both international and national levels, integrating pest prevention, surveillance, treatment, and certification systems. The International Plant Protection Convention (IPPC), under the Food and Agriculture Organization (FAO),

serves as the global authority for plant health protection and develops International Standards for Phytosanitary Measures (ISPMs) to harmonize trade practices among member countries. Among these, ISPM 15 is particularly significant for fumigation, as it regulates wood packaging materials used in international trade through approved treatments such as heat treatment and methyl bromide fumigation (Figure 4). The following diagram illustrates the hierarchical framework of phytosanitary regulations and highlights the major fumigation-related standards governing global trade compliance.

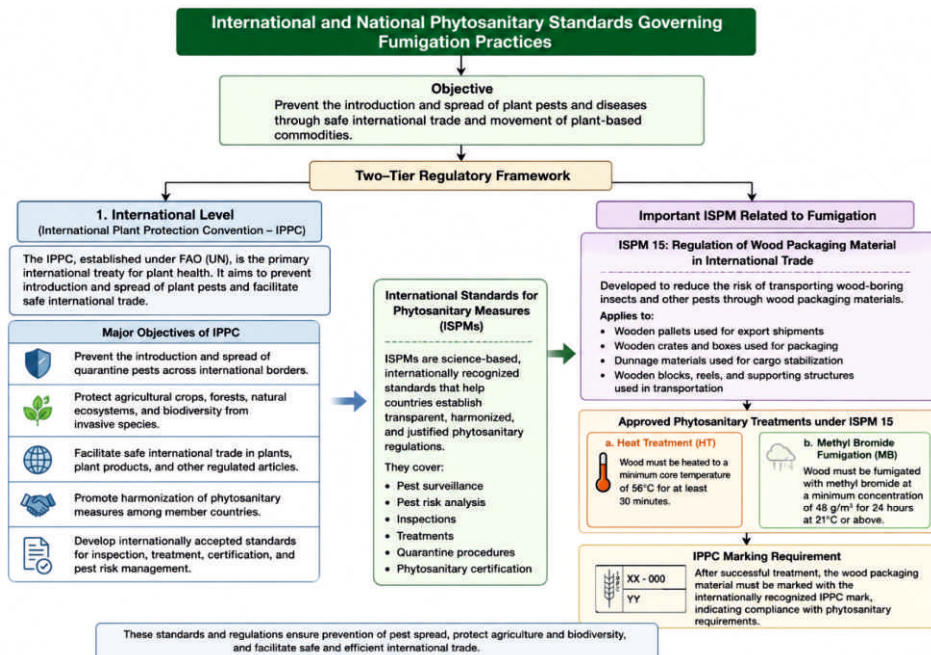


Fig. 4. Regulatory Framework of Phytosanitary Standards for Fumigation in International Trade (AI generated image)

National Standards for Phytosanitary Measures (NSPMs)

The National Standards for Phytosanitary Measures (NSPMs) provide the regulatory framework for implementing phytosanitary obligations at the national level, ensuring safe trade of agricultural commodities while preventing the spread of quarantine pests. In India, these standards are developed and enforced by the Directorate of Plant Protection, Quarantine and Storage (DPPQS) under the Ministry of Agriculture and

Farmers Welfare. Among them, NSPM 11 outlines the accreditation requirements for fumigation agencies to ensure technical competence and compliance with safety and operational standards, while NSPM 12 provides detailed procedures for quarantine fumigation, including pre-treatment inspection, fumigation operations, and post-treatment certification. The following diagram illustrates the structure, objectives, and operational workflow of NSPM-based fumigation practices in India (Figure 5).

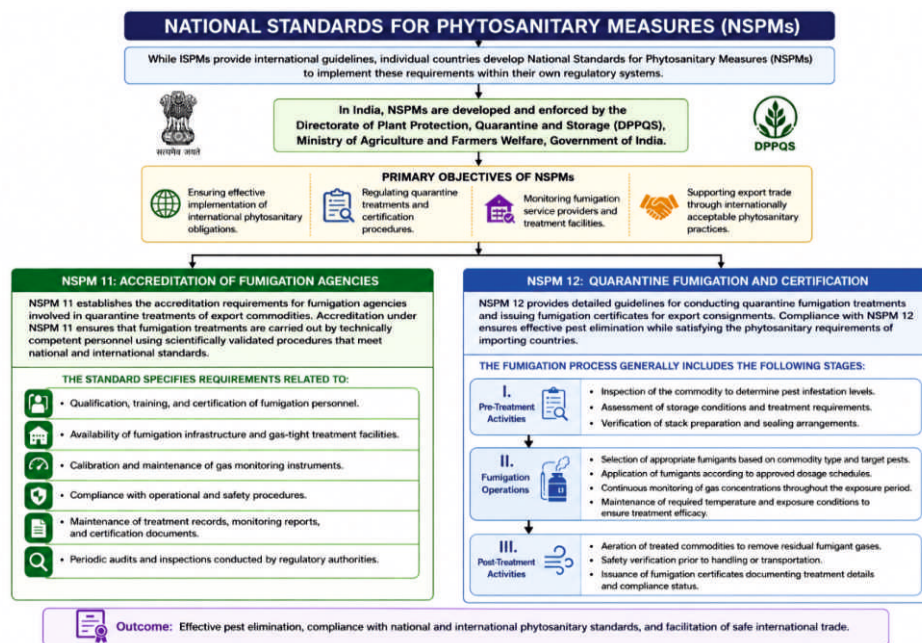


Fig. 5. Schematic Representation of Accreditation and Quarantine Fumigation Procedures under NSPMs (AI generated image)

Commonly Used Fumigants

Several fumigants have been utilized for stored-product protection, quarantine treatments and export certification. However, regulatory restrictions and environmental concerns have significantly influenced their usage patterns.

The major fumigants currently permitted or widely used include:

Phosphine (PH₃): Phosphine (PH₃) is one of the most widely used fumigants for the protection of stored commodities owing to its broad-spectrum activity against insects and rodents, excellent penetration capacity and low residue persistence.

Commercial phosphine is generated in situ from metal phosphide formulations such as aluminium phosphide

(AIP), magnesium phosphide (Mg₃P₂), calcium phosphide (Ca₃P₂), and zinc phosphide (Zn₃P₂) which release phosphine gas upon reaction with atmospheric moisture or acidic conditions.

After fumigation, phosphine is gradually oxidized to phosphate compounds, including phosphoric acid (H₃PO₄), thereby minimizing long-term environmental residues. The gas acts primarily by disrupting cellular respiration and energy metabolism in target organisms. However, phosphine has several limitations, including the need for prolonged exposure periods (typically 5-10 days) corrosive effects on copper and copper-containing alloys and increasing resistance among major stored-product insect pests. Furthermore, phosphine is highly toxic to humans and requires strict

safety precautions during handling. As phosphine gas is slightly denser than air, it may accumulate in poorly ventilated or low-lying areas, increasing the risk of occupational exposure. In addition, phosphine can form flammable or explosive mixtures with air at higher concentrations and may undergo spontaneous ignition under certain conditions, particularly when released rapidly from phosphide formulations, necessitating careful application and monitoring during fumigation operations. Recently government has put Aluminium Phosphide under 'RESTRICTED USE' category with remarks "The Pest Control Operations with Aluminium Phosphide may be undertaken only by Govt. /Govt. undertakings / Govt. Organizations / pest control operators under the strict supervision of Govt. Experts or experts whose expertise is approved by the Plant Protection Advisor to Govt. of India except Aluminium Phosphide 15 per cent 12 g tablet and Aluminum Phosphide 6 % tablet. The production, marketing and use of Aluminium Phosphide tube packs with a capacity of 10 and 20 tablets of 3 g each of Aluminium Phosphide are banned completely.

Methyl Bromide (CH₃Br): Methyl bromide (CH₃Br) is a colorless, odorless, highly penetrating fumigant that was extensively used worldwide for the control of stored-product insects, mites, nematodes, fungi, and other quarantine pests. Owing to its rapid mode of action and broad-spectrum efficacy, it became a preferred fumigant for stored commodities, soil sterilization, structural treatments, and quarantine and pre-shipment (QPS). Methyl bromide is recognized as a potent ozone-depleting substance, leading to its inclusion under the Montreal Protocol (1987), which mandated its phase-out for most agricultural and non-quarantine uses. Consequently, production and consumption were largely discontinued by 2005 in developed countries and by 2015 in most developing nations.

Methyl Bromide may be used only by Govt. /Govt. undertakings/Govt. Organizations / Pest control operators under the strict supervision of Govt. Experts or Experts whose expertise is approved by the Plant Protection Advisor (DPPQ).

Restricted Fumigants: Several fumigants that were widely used in the past have been restricted, phased

out, or banned because of concerns related to environmental safety, human health, residue issues, and occupational hazards. These include:

Ethylene Dibromide (EDB): Banned in many countries because of its carcinogenic and toxic properties.

Ethylene Dichloride-Carbon Tetrachloride (EDCT) Mixtures: Discontinued due to environmental and health concerns.

Carbon Disulfide (CS): Largely abandoned because of its high flammability and toxicity.

Hydrogen Cyanide (HCN): Severely restricted owing to extreme toxicity and safety risks.

Carbon Tetrachloride (CCI): Phased out because of its ozone-depleting properties and environmental impacts.

Crop-specific Chemical Recommendations

Chemical management varies depending on the crop and the associated pest species. In turmeric storage, periodic spraying of malathion on bags at 2–3month intervals have been recommended. Alternatively, Ethylene Dibromide (EDB) at 3 mL per 100 kg of rhizomes under airtight conditions can effectively prevent beetle infestation for up to one year (Malhotra, 2007). In coriander and fennel, the seed midge *Systole albipennis* can be effectively controlled through fumigation with methyl bromide (64 mg L⁻¹) or hydrocyanic acid gas at 27°C for two hours under reduced pressure.

Alternative Thermal and Microwave Treatments

Apart from chemical fumigants, physical approaches such as microwave and heat treatments have also shown promising results. Microwave exposure of eggs of *L. serricorne* and *S. paniceum* for 10 minutes prevented adult emergence in coriander seeds. Likewise, heat treatment combined with fumigation has been reported effective against *L. serricorne* infestations (Singh, 2007). These methods provide residue-free alternatives for pest suppression.

Modified atmospheres strategies for stored grain pest

Stored-product insects remain a major constraint to the safe storage of food grains causing significant quantitative and qualitative losses throughout the supply chain. Fumigation continues to be one of the

most effective pest management strategies for storage pest management, with phosphine being the predominant fumigant used globally due to its broad-spectrum efficacy and ease of application. However, the extensive and prolonged use of phosphine has resulted in the development of resistance in several key storage pest species, raising concerns about its long-term sustainability (Kaur *et al.*, 2022). Furthermore, the withdrawal of methyl bromide for most applications under the Montreal Protocol, because of its ozone-depleting effects, has narrowed the range of available fumigation options. Although several alternative fumigants, including sulfuryl fluoride, ethyl formate, carbonyl sulfide and ethanedinitrile, have shown promise, but their widespread adoption is often limited by regulatory and economic constraints. Consequently, residue-free technologies such as modified atmospheres (MA) and controlled atmospheres (CA) by utilizing different gases like carbon dioxide (CO₂), biogas, ozone (O₃) and nitric oxide (NO) are increasingly being explored as environmentally sustainable alternatives for stored-product pest management (Cao, 2019).

FHAT (Forced Hot Air Treatment)

Forced Hot Air Treatment (FHAT) is an effective non-chemical phytosanitary method used for disinfesting wooden packaging materials such as pallets, crates, and boxes. The process involves exposing wood to controlled high temperatures in a heat chamber to eliminate wood-boring insects, termites, molds, fungi and harmful microbes without using chemical fumigants. FHAT is considered an eco-friendly and safe alternative to chemical treatments and is widely accepted for export packaging. Untreated wooden materials may harbor pests and pathogens, posing risks during storage and international trade. To minimize these risks, heat treatment is mandatory under ISPM-15, while in India it is regulated under NSPM-9 by the Department of Plant Protection, Quarantine and Storage. In FHAT, wooden materials are heated until the core temperature reaches 56°C for at least 30 minutes, which effectively destroys all stages of insect pests and microbial contaminants. After treatment, the wood is certified and stamped for compliance. The major benefits of FHAT include

chemical-free disinfestation, prevention of pest re-infestation, improved durability of wooden packaging, enhanced hygiene and compliance with international phytosanitary standards, making it highly suitable for food, pharmaceutical, logistics and export industries (Anonymous, 2026).

Alternatives to conventional fumigants for stored-product pest management

With growing restrictions on methyl bromide and the widespread development of phosphine resistance, several alternative fumigation strategies have been investigated for protecting stored commodities. These alternatives differ in their mode of action, persistence, commodity compatibility, and safety profiles.

Volatile fumigants: Among rapid-action volatile fumigants, ethyl formate (EF) and propylene oxide (PPO) have demonstrated strong potential. EF, commercialized as Vapormate®, achieved nearly complete mortality of phosphine-resistant *R. dominica* at 450 g m⁻³, with residues declining to natural levels within seven days in cereals (Haritos *et al.*, 2006). PPO, widely used for sterilization of spices and nuts, showed complete insect mortality at 45 mg L⁻¹ within 48 h (Zettler *et al.*, 2002). Both fumigants act rapidly but their flammability remains a practical challenge.

Fluoride-based fumigants: Fluoride-based fumigants, particularly sulfuryl fluoride (SF), are increasingly recognized for managing phosphine-resistant insects. SF is highly effective against resistant populations of *T. castaneum* and *R. dominica* (Opit *et al.*, 2012). Since eggs are comparatively more tolerant, exposure duration and temperature become critical factors in treatment optimization. Synergistic combinations of SF with phosphine further improved control of resistant strains (Jagadeesan *et al.*, 2021).

Sulfur-based fumigants: Among sulfur-based fumigants, carbon disulphide (CS₂) represents one of the earliest options used in grain protection. It was reported effective against major storage pests such as *S. oryzae*, *R. dominica* and *T. castaneum* at concentrations of 6-10 mL L⁻¹ within 24 h (Shaaya *et al.*, 1998). However, residue persistence, high flammability, and negative impacts on seed viability and flour quality restrict its commercial acceptance. Carbonyl sulphide (COS) another sulfur-based

fumigant, has gained attention because of its broad-spectrum efficacy and lower impact on grain quality. A product of 1650-1950 mg/h/L⁻¹ effectively controlled multiple storage pests without significantly affecting germination, bread quality, or oil content (Wright, 2003).

High-toxicity alternatives: High-toxicity alternatives such as methyl iodide (MI), and ethane dinitrile (EDN) have also shown promise. EDN has demonstrated excellent penetration and rapid desorption, making it highly effective even against tolerant egg stages of storage insects (Ramadan *et al.*, 2020). However, operator safety and phytotoxicity concerns require careful consideration.

Others: In addition to chemical fumigants, modified atmosphere treatments such as ozone (O₃) provide an eco-friendly alternative. Ozone acts through oxidative stress, damaging insect cell membranes and DNA (Sousa *et al.*, 2013). Its effectiveness against *S. oryzae*, *R. dominica*, *T. castaneum*, and *C. maculatus* demonstrates its strong potential as a residue-free grain disinfestation tool (Pandiselvam *et al.*, 2019). This makes ozone particularly attractive for sustainable storage systems.

Botanical management of stored grain pests in seed spices

Stored seed spices are highly vulnerable to infestation by a complex of insect pests and mites during storage, resulting in severe quantitative and qualitative losses. The major pests include the cigarette beetle (*Lasioderma serricorne*), drugstore beetle (*Stegobium paniceum*), red flour beetles (*Tribolium spp.*), granary weevil (*Sitophilus granarius*), rice weevil (*Sitophilus oryzae*), pulse beetles (*Callosobruchus spp.*), and storage-associated mites. These pests not only reduce seed weight and quality but also adversely affect germination, vigour, marketability, and safety of seed spices.

Botanical Pesticides: A Sustainable Alternative to Synthetic Insecticides

The growing concern over pesticide residues, insect resistance, and environmental hazards has intensified the search for safer alternatives. Botanical pesticides have gained considerable attention due to their rapid biodegradability, lower persistence and reduced

toxicity to non-target organisms. Their active compounds are readily degraded by detoxifying enzymes and rapidly disintegrate in plant systems, air and moisture, thereby minimizing environmental contamination (Lengai *et al.*, 2020). Consequently, plant-derived products such as powders, oils, and leaf extracts are considered safer for both human health and ecological sustainability (Ukoroije and Olayor, 2020; Farooqui *et al.*, 2005).

Seed Spice-Derived Essential Oils as Self-Protective Botanical Agents

An innovative strategy in storage pest management involves utilizing essential oils extracted from seed spices themselves. Seed surface impregnation with fixed oils of coriander (*C. sativum*), cumin (*C. cyminum*), fennel (*F. vulgare*) and ajwain (*T. ammi*) significantly suppressed population development of *L. serricorne*. Among these, fennel oil provided maximum protection by substantially reducing beetle multiplication during prolonged storage with efficacy increasing at higher oil concentrations (Kant *et al.*, 2022). This concept of “self-derived protection” represents a novel and sustainable approach for stored seed spice preservation.

The insecticidal properties of fennel have been linked to its major volatile constituents, namely (E)-anethole, estragole, and (+)-fenchone. These compounds exhibit both contact and fumigant toxicity. Kim and Ahn (2001) reported complete mortality (100%) of *L. serricorne* at 0.105 mg cm⁻² of (E)-anethole within 24 h. Enhanced efficacy under closed fumigation conditions further confirmed the importance of vapor-phase toxicity. In addition, fennel essential oil showed strong acaricidal activity against spider mite, *Tetranychus urticae* (LC₅₀ = 0.557% contact; 1.876 µL L⁻¹ air fumigant) (Ebadollahi *et al.*, 2014), while (+)-fenchone was effective against *Dermatophagoides spp.* (LD₅₀ = 38.9 mg m⁻²) (Lee, 2004).

Broad-Spectrum Plant Extracts for Storage Pest Suppression

Lantana camara leaf essential oil exhibited excellent fumigant (LC₅₀ = 4.141 mg L⁻¹ air) and contact toxicity (LC₅₀ = 4.82 mg cm⁻²) against *L. serricorne*, along with significant repellent activity Aisha *et al.* (2024).

Neem-based formulations have shown broad-

spectrum toxicity against *Tribolium castaneum*, *Sitophilus oryzae* and *Callosobruchus chinensis*. Aslam *et al.* (2026) reported mortality rates of 94 per cent and 89 per cent in *T. castaneum* and *S. oryzae*, respectively, at 10% concentration after 72 h. Neem seed kernel powder and oil also effectively reduced adult emergence and seed damage in *C. chinensis* (Sharma *et al.*, 2013).

Black Pepper (*Piper nigrum*) has demonstrated strong toxicity against *S. oryzae* and *Callosobruchus maculatus*, largely due to piperine and volatile alkaloids (Su, 1977). It was also reported as the most effective botanical against *C. chinensis* among several plant materials tested (Zia *et al.*, 2011).

Coriander (*Coriandrum sativum*): Coriander essential oil exhibited strong fumigant activity, particularly against *C. maculatus* ($LC_{50} = 1.34 \mu\text{L L}^{-1}$ air), compared to *Tribolium confusum* ($318.02 \mu\text{L L}^{-1}$ air), indicating species-specific sensitivity (Khani and Rahdari, 2012). Ajwain (*T. ammi*) and dill (*Anethum graveolens*) essential oils have shown both acute toxicity and developmental inhibition. Chaubey (2007) reported LC_{50} values of 11.62 and 14.78 μL for larvae and 13.48 and 16.66 μL for adults for ajwain and dill, respectively. Both oils also inhibited larval-to-pupal transformation, with EC_{50} values of 6.70 μL (ajwain) and 7.86 μL (dill). Soltani *et al.* (2024) further confirmed the fumigant efficacy of dill oil, with LD_{50} values declining from 232.89 to 132.57 $\mu\text{L L}^{-1}$ air between 12 and 24 h. Major constituents included dillapiole (37.86%), carvone (22.59%), and trans-isolimonene (10.01%).

Recent evidence further strengthens the insecticidal potential of cumin (*Cuminum cyminum*) and ajwain (*Trachyspermum ammi*) essential oils against the rice weevil, *Sitophilus oryzae*, one of the most destructive pests of stored cereal grains. Ebadollahi (2025) reported that the major bioactive constituents of cumin essential oil included β -pinene, cumin aldehyde, cymene, and γ -terpinene, whereas ajwain essential oil was dominated by cymene, thymol, γ -terpinene, and α -pinene. Both essential oils exhibited strong fumigant toxicity, with 24 h LC_{50} values of 100.89 $\mu\text{L L}^{-1}$ and 172.48 $\mu\text{L L}^{-1}$ air for cumin and ajwain, respectively, indicating comparatively higher toxicity of cumin oil. Sublethal exposure at LC_{30} concentrations (74.28 and

130.31 $\mu\text{L L}^{-1}$ air for cumin and ajwain, respectively) significantly prolonged the developmental duration of immature stages and extended the pre-oviposition as well as total pre-oviposition periods of adult insects. Moreover, both essential oils markedly reduced fecundity, adult longevity, and key population growth parameters, including intrinsic rate of increase (r), net reproductive rate (R_0), gross reproductive rate (GRR), and finite rate of increase (λ).

Nano-emulsion Technology for Storage Pest Management

Nano-emulsion technology has emerged as a promising innovation in stored-product pest management, particularly as an advanced delivery system for botanical insecticides and essential oils. Nano-emulsions are thermodynamically or kinetically stable colloidal dispersions consisting of oil droplets ranging from 20 to 200 nm in diameter dispersed in an aqueous phase with the aid of surfactants. Their nanoscale dimensions enhance the stability, bioavailability, controlled release, and persistence of bioactive compounds, thereby improving insecticidal efficacy while minimizing environmental contamination and adverse effects on non-target organisms. Compared with conventional crude oils, nano-emulsion-based formulations have consistently exhibited superior insecticidal activity against major storage pests. Pulegone-loaded nano-emulsions caused more than 90% mortality of *Sitophilus oryzae* and *Tribolium castaneum* over a five-week storage period, indicating prolonged residual activity and enhanced persistence (Golden *et al.*, 2018). Similarly, eucalyptus oil nano-emulsions significantly enhanced toxicity by reducing LC_{50} values by 19–79% compared to crude oil formulations (Adak *et al.*, 2020). Nano-emulsions of Vitex negundo further demonstrated improved potency, reducing LD_{50} values by 41.60% against *S. oryzae* and 29.88% against *T. castaneum* relative to non-encapsulated extracts (Mishra *et al.*, 2024). Beyond direct mortality, nano-emulsions have also shown substantial effects on progeny suppression and grain protection; for instance, anise (*Pimpinella anisum*) nano-emulsion reduced progeny emergence by 94.64 per cent and provided 84.5 per cent protection of stored grains (Draz *et al.*, 2022). Likewise, rosemary

and black seed nano-emulsions exhibited significantly enhanced toxicity against *Sitophilus granarius*, with LD₅₀ values of 102.56 and 35.08 µg g⁻¹, respectively, substantially lower than those of the corresponding crude oils (Ali *et al.*, 2022). Collectively, these findings underscore the immense potential of nano-emulsion technology in enhancing the delivery efficiency and insecticidal performance of botanical products, making it a highly promising and sustainable strategy for the management of stored-product insect pests.

Conclusion

The storage pests pose a serious threat to the quality, viability and market value of seed spices by causing significant quantitative and qualitative losses during storage. Effective management requires an integrated approach combining preventive measures, early detection, chemical fumigation, modified atmosphere techniques and botanical alternatives. While phosphine remains the most widely used fumigant,

resistance development and regulatory restrictions highlight the need for sustainable alternatives. Emerging technologies such as hermetic storage, nano-emulsion-based botanicals, ozone, and controlled atmospheres offer promising eco-friendly solutions. Future emphasis on integrated pest management (IPM), advanced diagnostic tools and safer bio-based fumigants will be crucial for ensuring long-term storage security, food safety and export quality of seed spices.

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Conflict of Interest

The authors declare that they have no conflict of interest.

Table 2. Botanical extracts active against *Lasioderma serricorne*

Botanical source	Mode of action against <i>L. serricorne</i>	Key findings	Reference
<i>Elsholtzia stauntonii</i> (Benth.)	Fumigant toxicity	99.32% larval mortality and 97.97% adult mortality at 40 µL/L air after 48 h.	Lu <i>et al.</i> (2012)
<i>Rosmarinus officinalis</i> (Rosemary)	Fumigant toxicity	91.76–100% mortality after 72 h exposure.	Ren <i>et al.</i> (2022)
<i>Eucalyptus</i> spp.	Fumigant toxicity	91.76–100% mortality after 72 h exposure; 100% mortality in stored turmeric within 3–7 days.	Ren <i>et al.</i> (2022); Naveena <i>et al.</i> (2021)
<i>Ocimum basilicum</i> (Basil)	Fumigant toxicity	91.76–100% mortality after 72 h exposure.	Ren <i>et al.</i> (2022)
<i>Cymbopogon nardus</i> (Citronella)	Fumigant toxicity	91.76–100% mortality after 72 h exposure.	Ren <i>et al.</i> (2022)
<i>Pelargonium graveolens</i> (Geranium)	Fumigant toxicity	91.76–100% mortality after 72 h exposure.	Ren <i>et al.</i> (2022)
<i>Parthenium hysterophorus</i> L. (Parthenium)	Contact and fumigant toxicity	Highest contact toxicity (LD ₅₀ = 3.762 µl/ml) and fumigant toxicity (LC ₅₀ = 4.262 µl/ml air).	Latif (2023)
<i>Azadirachta indica</i> (Neem)	Contact toxicity / insecticidal activity	100% mortality in stored turmeric within 3–7 days.	Naveena <i>et al.</i> (2021)
<i>Citrus hystrix</i> DC.	Fumigant toxicity	98.75% fumigant toxicity against pupae at 60 ppm.	Ikawati <i>et al.</i> (2017)
<i>Artemisia lavandulaefolia</i> DC. (Davana)	Contact and fumigant insecticidal activity	Chamazulene identified as the principal bioactive constituent responsible for strong insecticidal activity.	Zhou <i>et al.</i> (2018)

Table 3. Botanical extracts for management of other stored insects of seed spices

Botanical source	Target insect(s)	Mode of action / effect	Key findings	Reference
<i>Azadirachta indica</i> (Neem)	<i>Tribolium castaneum</i> ; <i>Sitophilus oryzae</i>	Insecticidal activity	94% mortality in <i>T. castaneum</i> and 89% mortality in <i>S. oryzae</i> at 10% concentration after 72 h.	Aslam <i>et al.</i> (2026)
<i>Azadirachta indica</i> (Neem)	<i>Tribolium castaneum</i>	Insecticidal activity	65.55% mortality in <i>T. castaneum</i> .	Krishna & Yadav (2023)
<i>Azadirachta indica</i> (Neem)	<i>Sitophilus oryzae</i> ; <i>Sitophilus granarius</i>	Insecticidal activity	70% mortality in rice weevil and 56.7% mortality in granary weevil.	Rahaman <i>et al.</i> (2020)
<i>Polygonum hydropiper</i> (water pepper)	Different pulse beetles	Insecticidal activity	100% mortality of pulse beetles.	Rahaman <i>et al.</i> (2020)
<i>Syzygium aromaticum</i> (Clove)	<i>Tribolium castaneum</i>	Insecticidal activity	76% mortality.	Nikolaou <i>et al.</i> (2021)
<i>Allium sativum</i> (Garlic)	Stored-product insects	Insecticidal activity	36–62% mortality.	Nikolaou <i>et al.</i> (2021)
<i>Cinnamomum</i> spp. (Cinnamon)	Stored-product insects	Insecticidal activity	Demonstrated effective insecticidal activity.	Nikolaou <i>et al.</i> (2021)
<i>Citrus</i> spp. volatile oil	<i>Sitophilus oryzae</i>	Fumigant/contact toxicity	100% mortality within 24 h.	Chayengia <i>et al.</i> (2010)

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