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10. Storage Insect Pests and Their Management

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Abstract:

Stored product pests pose a threat to grain storage from the field to processing, with approximately one thousand insect species globally associated. While numerous insects are linked to stored goods worldwide, only a few are causing significant damage to stored grains. Quantitative losses of stored grain vary globally, impacting both developed and undeveloped countries. Food stored in bags and bins is particularly susceptible to infestation, leading to extensive post-harvest losses, spoilage, reduced market demand, and economic crisis. Effective management of stored grain pests is imperative to mitigate these challenges. Current management approaches aim to address these issues through preventive practices, monitoring, sanitation, and management measures. Stored grain insect pests are categorized based on feeding behavior and damage severity, guiding insect management decisions. Common pests include grain weevils, grain borers, grain moths, flour moths, mealworms, grain and flour beetles, Drug store beetle, cigarette beetle, mites, and potato tuber moth. To reduce losses from storage insect pests, diverse management strategies, such as physical, biological, botanical, chemical, host plant resistance, nanotechnology, molecular techniques and integrated pest management methods are essential for effective control.

Keywords:

Stored grain, internal, external, secondary, temperature, infestation, damage, botanicals, integrated pest management

10.1 Introduction:

Technological advancement and modernization in agriculture improved the production, supply and distribution of food grains globally. Thus, a large portion of the food grains produced are stored for regular availability and contingency in many countries. This long term stored products were prone to several direct and indirect losses in storage structures by both biotic and abiotic agents. Among biotic factors, insects cause notable damage, which accounts for nearly 10-20 per cent of the total storage losses affecting food safety and security (Phillips and Throne, 2010). Nearly 600 species of coleopterans, 70 lepidopterans and 355 mite species were reported to feed on the stored products (Rajendran and Sriranjini, 2008). Reduction in grain weight, germination and nutritional value causes direct damage to storage produce and insect presence their faeces contaminate the grains causing indirect losses. Insect pests are either carried over from the field or moved from older infestations leading to their establishment in the storage site. Old bags and storage containers are major sources of attack along with the cross over infestation (Pruthi and Singh, 1950). Majority of the storage pests are distributed globally in many parts causing similar kinds of damage although the severity of infestation varies based on the grain type and region of warehouse (Tyagi *et al*., 2019). Based on the severity of damage in particular region, storage insects can be classified into major and minor pests.

10.2 Classification of Storage Pests:

Based on their feeding habits, storage insects are classified as 'primary pests' and 'secondary pests'. Primary pest attacks whole grain and their larval stages enter into the whole grain and feed on the inner starchy contents leading to hidden infestation. They are difficult to manage, and regular monitoring is needed to control them. Secondary pests are called "bran bugs" due to their feeding behaviour. They attack the grains which are already damaged by other organisms (Bell, 2014).

Secondary pests feed on the broken kernels, grain debris and bran. They can be easily identified in the lot due to their active larval stages feeding on the external surface. Some are fungal feeders feeding on the moulds developed due to the primary infestation and high moisture conditions e.g., mites and pscocids (Magan *et al*., 2003)

Based on the feeding behaviour, storage insects were also grouped as external and internal feeders. External feeding insects feed externally on the endosperm and germ layer. They either feed on whole grains or damaged kernels. e.g., khapra beetle, Indian meal moth, rice moth. Internal feeders lie inside and feed on the internal portion of seed reducing the germination value. They are not easily detectable leading to heavy losses e.g., rice weevil, granary weevil, pulse beetle.

An Overview of Important Pests Infesting Storage Products:

10.2.1 Grain Infesting Insect Pests:

A. Rice Weevil, *Sitophilus oryzae* (Curculionidae: Coleoptera):

Identification marks: White translucent eggs. Fleshy fully grown larva measures 5mm in length with no legs. The adult weevil is reddish brown with 3mm length and a curved rostrum with an antenna at the base. Strong jaws are present on the rostrum. Adults can be distinguished by the presence of four reddish or yellowish spots present on the elytra. Both female and male adults look alike except for the rostrum which is short and broad in males.

Hosts: Rice, wheat, millets, barley, corn, sorghum, dried seeds, nuts, pasta and flour

Economic Importance: Rice weevil is a cosmopolitan insect on stored paddy and possesses polyphagous feeding nature.

Nature of damage: Each adult female weevil lays about 350 eggs inside the grain after four days of emergence by making a slit like opening. The slit was further sealed with glue like secretion from ovipositor. In warm and humid weather, eggs hatch in three to four days and six to ten days in cooler regions.

Grub feeds on the inner starchy kernel portion of the grain and pupates in 25- 30days. Resting pupal stage lasts for 3-5 days leading to adult emergence.

Rice weevil damages the grain more than what it feeds leading to heavy qualitative and quantitative losses. In most cases, infestation is carried from the field to the storage site where they are established.

B. Lesser Grain Borer, *Rhyzopertha Dominaca* (Bostrychidae: Coleoptera):

Identification marks: White coloured eggs. Larva covered with body hairs and brown anterior head. Adults are small, dark-coloured beetles with a rough elytrum.

Hosts: Infests cereals like stored paddy, wheat, barley, maize and sorghum during preharvest and postharvest attacking both in the field and warehouse

Economic Importance: Native to India, later spread to other countries. It is considered as a serious pest next to rice weevil in storage.

Nature of damage: Adults lay eggs on the grain surface where young larva can easily penetrate the grain. After hatching, larvae enter into the grain and starts feeding which lasts for 38-40 days depending on the temperature. Young larvae feeds on the debris and frass resulting from the older larval feeding. Heavily infested lots become powdery with leftover bran and kernels with only pericarp left. Adults are good flyers which increases the further spread of insect to new lots (Birch *et al*., 1945)

C. Khapra Beetle, *Trogoderma Granarium* (Dermestidae: Coleoptera):

Identification marks: Single or clustered translucent eggs. Larval body is covered with several erectile moving hairs. Oval shaped tiny beetle with head hidden underneath the hood like pronotum. Markings on the elytra present.

Hosts: Major pest of wheat grains also feeds on corn, jowar, paddy, sorghum, oilseeds and pulses.

Economic Importance: Serious pest on several cereals and oilseeds particularly in warmer regions.

Nature of damage: A single adult lays nearly 110-120 eggs on the external surface of the grain. Larva after emergence feeds on the debris and broken grains.

In most cases, infestation is noticeable, as they feed on the superficial surface of lots. Under heavy infestation, grubs enter to the deeper layers and damage the whole lots.

Only larvae cause damage to the grains reducing the germination value (Shafique and Chaudry, 2007)

D. Pulse Beetle, *Callosobruchus maculatus* (Bruchidae: Coleoptera):

Identification marks: Creamy white eggs. Larva is cylindrical with no legs and wrinkled body. Adult beetle possesses white patched on the elytra with a prominent elytrum and an exposed pygidium.

Hosts: Pea, chickpea, black gram, pigeon pea, horse gram, cowpea and other pulses

Economic Importance: Important pest in storage and field for legumes mainly in the Indian subcontinent.

Nature of damage: Adult female lays 80-100 eggs glued on to the exterior of pulse seeds. Emerged larvae enter the seed and feeds on the endosperm reducing the germination percentage and pupates in 15-20 days. Infestation can be identified by the presence of glued white eggs and flappy seeds with holes.

E. Angoumois Grain Moth, *Sitotroga cereallela* (Gelechiidae: Lepidoptera)

Identification marks: White coloured larvae. Adults are small with brownish wings with hairs on the hind wings.

Hosts: Paddy, wheat, sorghum, bajra and other cereals

Economic Importance: Serious pest on warm temperate regions. Infestation starts in the field during milk stage and establishes in the warehouses during storage.

Nature of damage: Adult female lays about 150-300 eggs on the grain surface. Young larva bores the grain then feeds on the endospermic content for 100-120 days. Larvae spins the cocoon inside the grain and pupates. Pupal period lasts for 10-12 days.

F. Rice Moth, *Corcyra cephalonica* (Pyralidae: Lepidoptera):

Identification marks: Creamy white larva with a prominent brownish yellow head. Adult females are larger in size compared to males.

Hosts: Wheat, barley, corn, sorghum, millets and oilseeds

Nature of damage: Larvae feeds on the broken grains in the initial stages and feeds on the whole grains in the later stages. Besides feeding, larvae leave frass, debris and makes webbing in the grain lot reducing the grain quality.

10.2.2 Flour Infesting Pests:

A. Rust Red Flour Beetle/Red Flour Beetle, *Tribolium Castaneum* (Herbst) (Tenebrionidae: Coleoptera)

Economic importance: Cosmopolitan pest and can infest all kinds of stored commodities. Serious pest in flour mills.

Identification marks: Adults are reddish brown coloured, flat, and measure 5–6 mm in length. Last segment of antenna is much larger (club shaped) than the previous one.

Host: It feeds on wide range of hosts like cereals, flour, nuts, oats, rice bran and other processed foods. Chocolate, almonds, dried fruit, spices, oilseed cake, and even animal bones are among the other things are targeted.

Biology: The yellowish white coloured early instar larvae measured 1 mm long. It turns into a reddish yellow colour as it ages. The pupal stage lasts for five to nine days. An adult female lay 400 - 450 eggs. Eggs were glued on the top of grains or detritus. These are tiny, cylindrical, wheatish-colored, rounded at both ends and need 5–10 days for incubation. This highly active larvae pupate after three to four weeks. Pupation occurs on the grain surface and lasts for seven to eight days. Adults live for four to five days and feed continuously.

Nature of damage: Polyphagous. This pest typically causes a loss in both quality and quantity. Adults are active individuals that are typically hidden within flour products. As they pass through the flour and other granular food products, adults build tunnels.

B. Indian Meal Moth*, Plodia Interpunctella* (Phycitidae: Lepidoptera):

Economic importance: An important cosmopolitan economic insect pest of stored goods is the Indian meal moth. Reduces the export value by causing indirect damage to the grains.

Identification marks: Its unique forewing markings make it easy to identify from other grain pests. These markings are whitish grey on the inside and brownish on the surface. The long, silvery grey hind wings have silky fringes. Thorax has reddish-brown scales and is marginally darker.

Host: Cereal flour, animal feed, dried nuts and other processed foods.

Biology: Every female moth lays across 100 and 300 eggs on or near adequate food, either individually or in clusters. The egg period lasts anywhere from two days to two weeks, depending on the climate. When the larva reaches maturity, it turns light brown in the head and is typically white with pink or green. It has a length of 8-3 mm. It takes the larvae 30 to 35 days to reach full growth.

Nature of damage: Larval consumption on the food source and an abundance of silken web-spinning are what causes the damage. Although the webs safeguard the larvae from desiccation, they also draw in excrement, cast larval skins, and faecal pellets, which causes far more contamination than the actual feeding.

C. Yellow Meal Worm, *Tenebrio Molitor* L. (Tenebrionidae: Coleoptera):

Economic importance: The largest and most cosmopolitan pest species that attacks the stored grains and their processed products.

Identification marks: It is commonly referred to as the darkling beetle, is a smooth, dark-brown or black insect with longitudinally striated or grooved forewings and a finely punctured thorax.

Host: It primarily prefers decaying grains, milled cereals and foodstuffs. It will also consume mealbran, bread and preserved insects.

Biology: About 300–500 white, bean-shaped eggs are laid. Larvae are cylindrical, and white in the young stages and turns yellow as they mature. Some larvae undergo hibernation in harsh environments.

D. Saw Toothed Grain Beetle, *Oryzaephilus Surinamensis* (Coleoptera: Silvanidae*):*

Economic importance:

This is typically found in warm environments and feeds on starchy foods. The reason for its common name is its typical thoracic structure, which has six projections on each side that resemble teeth.

Identification marks: slender dark brown flattened beetle with six saw like teeth on both sides of prothorax. Eleven segmented antennas.

Host: Pest on grain and grain products, commonly found in flour mills and grocery stores.

Biology: The female deposits six to ten tiny, white eggs per day loosely in the food or in cracks and crevices of warehouses. Adults last six to eight months causing severe damage.

Nature of damage: Larvae consume starchy food or the endosperm of broken grains. The main signs of this pest infestation are the development of cocoons and larvae.

E. Long Headed Grain Beetle, *Latheticus Oryzae* (Tenebrionidae: Coleoptera):

Economic importance: Widespread in distribution. Feeds on plant and animal stored products in grainaries and mills.

Identification marks: Slender, pale yellow coloured, flat beetle with a slightly bulg in the antennae.

Host: Broken cereal grains, cereal flour and barley.

Biology: Smooth translucent eggs. Grubs have creamy white skin with dark eyes. The larval body is covered with pale-colored hairs. Lifecycle is completed in 25 to 39 days in warm conditions.

Nature of damage: Both grubs and adults cause serious damage. Secondary infestation occurs in stored rice, wheat, and other grains.

F. Almond Moth, *Ephestia Cautella* (Phycitidae: Lepidoptera):

Economic importance: The fig moth, or almond moth, is a widespread insect in tropical and subtropical regions.

Identification marks: The adult moth is about nearly three quarters the size of *C. cephalonica* and has a dark band on its forewings. Its body is gray in color, and when it is at rest, its forepart is raised, giving the wings an apparent slope.

Host: Dried fruits and figs, rough rice, wheat, sorghum, soybeans, and some oilseeds.

Biology: Each female lays between 200 and 250 eggs, which are randomly dispersed on the grain lots and cracks.

Eggs hatch in 3-4 days. When the larvae reach maturity, they spin a lot of silk and produce tiny silken tubes inside the grain or between food particles, where they remain lodged.

Nature of damage: Larvae are indicative of an infestation. Inside the grain, the larvae dig tunnels.

G. Psocids:

Economic importance: Commonly found in old books. Psocids feeds on the starchy paste used in book binding.

Identification marks: Small, soft-bodied, louse like insects with long, thin antenna. Female lays eggs mostly on leaves or in cracks. Nymphs must go through six molts in order to mature. Booklice vary in length from 1 to 2 mm.

Host: Although this pest primarily feeds on grains, bookbinding, lichen, algae, and other organic detritus found in nature, it is additionally thought as a stored grain pest.

Biology: Warm, humid environments with a temperature of 25°C and a relative humidity of 75% are favourable. Life cycle lasts for 24 days.

Nature of damage: In addition to causing damage to books, they occasionally infest areas used for storing food, where they feed on dry, starchy materials. Some psocids feed on forest trees. They have little to no interaction with people, making them unimportant economically. Since they are scavengers, booklice seldom bite people.

10.2.3 Non-Insect Pests:

A. **Mite,** *Acarus siro*; *Tyroglyphus* spp.; *Carpoglyphus lactis; Glycyphagus domesticus* (Acaridae: Acarina) (Class: Arachinida):

Identification: Mites are tiny, soft-bodied creatures with a microscopic nature. Their coloration typically ranges from pale straw to dark reddish-brown.

Host: These mites primarily targeting stored grains and rapidly multiply within a short timeframe. Nearly all plant species and stored seed or grain materials can be impacted by mites.

Economic importance: Mites are important pests of mills. They are microscopic in size and exhibit a cosmopolitan distribution.

Biology: With a propensity for infesting both crops directly and indirectly, these mites proliferate swiftly.

The shedding of their skin leads to the buildup of fluffy, bright brown masses beneath sacks containing food grains.

Nature of Damage: These mites are known to harm the germ portions of wheat. Under heavy infestation, they induce sweating and impart musty odour to the grains. Additionally, their feeding activities contribute to damage, evident through decoloration or fading.

B. Rodents (Muridae: Rodentia) (Class: Mammalia):

Identification:

- **House Rat:** *Rattus rattus* Linn. Adult weight: 100-300 g; Body length: 145-200 mm. Body is slender, medium sized with pointed nozzle. Ears are large, prominent, thin stands out from fur. Faecal pellets are elongate, pointed and bean shaped.
- **House mouse:** *Mus musculus* Linn. Adult weight: 12-16 g; Body length: 80-100 mm. Body is slender, small sized with small, pointed nozzle. Ears are prominent, large for size of it. Faecal pellets are spindle shaped.
- **Norway rat or Brown rat**: *Rattus norvegicus* Birk. Adult weight: 100-500 g; Body length: 200-270 mm. It has heavy thick body with blunt nozzle. Ears are small, close set, half buried in fur. Faecal pellets are blunt and rectangular.
- **Field Rats:** *Bandicota bengalensis* Gray. Adult weight: 234-237 g. Body length: 36-41 cm.
- **Large bandicoot:** *Bandicota indica* Bech. Adult weight: 800-1000 g; Body length: 470-560 mm. It has heavy thick body with slightly pointed nozzle. Ears are thick and small. Faecal pellets are oval and bulky.

Host Plants: Rats exhibit a high degree of polyphagy, consuming various stored food materials and also causing damage to diverse field crops.

Biology: Rats exhibit prolific breeding habits, commencing reproduction at 3 to 4 months of age and persisting year-round. Under favourable conditions, a female can produce upto 10 offspring per litter, with a frequency of 10-12 times annually. As a result, a single rat pair has the potential to generate around 800 offspring per year, with a lifespan spanning 3 to 5 years.

Economic importance: Rats hold significant economic importance due to their diverse involvement in human food and health issues. Storage-related losses amount to an annual average of 2.5% attributable to rodent-related problems.

Nature of Damage: Rats are causing significant damage to stored grains by nibbling on earheads and feeding on developing grains in standing crops. They transport grains to their burrows and also causing significant damage on threshing yards and godowns. It has been noted that the house rats can consume about 10 g of food grains per day, while bandicoots consume 15g.

On average, a rat consumes around 10 g of grains daily, in addition to other forms of damage. A population of 100 rats, excluding their progeny, has the potential to damage approximately one tonne of grains in a year. The impact on field crops may result in damage ranging from 5 to 25 percent.

10.2.4 Miscellaneous:

A. Sweet Potato Weevil, *Cylas Formicarius* (Apionidae: Coleoptera):

Identification marks: The adult is antlike, slender, and shiny black with thorax and legs are being in red colour. Adult is sluggish and live for about 3 months.

Host: Sweet potato

Biology: Oval, yellowish-white eggs laid singly in small cavities on the sweet potato root or tuber or in stem. The cavity is then sealed with a plug made from the mother's feces. White grub with no legs, feed on tissue and leaving the hole of entry. The head is relatively large and brown or pale yellow. Pupae are whitish in color and pupate in the feeding tunnel. Weevils are beetles with long pointed snouts and slender bodies similar to ants.

Nature of damage: Vines becoming thicker and more distorted, with frequent tissue cracking. Wine damage can manifest as discoloration, cracking, or wilting. Cavities and tunnels are common features of an infested tuber. Attacked tubers turn spongy, brown to black in color, and begin to rot from the top. They also acquire an unpleasant taste and smell unfit for ingestion by humans.

B. Cigarette Beetle, *Lasioderma Serricorne* (Anobiidae: Coleoptera):

Identification marks: The adult is a tiny, 2.5 mm-long, round, reddish-brown beetle with minute hairs on elytra. Head with hidden antennae projected downward. Adults are able to fly freely.

Host: Several hosts, but mostly cocoa, chocolate, tobacco leaves, and spices. It is a severe tobacco pest.

Economic importance: Cosmopolitan pest, it favors warm climates. In temperate and subtropical locations, insects are active year-round in warm buildings and during the winter, their development slows down.

Biology: The eggs are mostly oval and creamy white in color. Females can lay approximately 100-110 eggs, hatch in 5-6 days. The larval stage lasts for about 20-25 days. Newly hatched grub is smaller than the adults and very active, worm-like, they live inside tobacco. Grubs are scarabaeiform and less active. The pest causes damage by constructing small gallerias. The pupa is glossy white at first which gradually turns into reddish-brown after a few days.

Nature of damage: The adults and grubs invade tobacco products, such as chewing tobacco, cigarettes, and Cheroots. The presence of round, pin-sized hole on processed tobacco is a common sign.

C. Drug Store Beetle, *Stegobium Paniceum* (L.) (Anobiidae: Coleoptera):

Economic importance: More severe pest in temperate than in tropical and it is almost cosmopolitan in nature.

Identification marks: Adults are smaller than *L. serricorne*, reddish brown, striated elytra and have a short lifespan. It is a long, cylindrical, light brown insect with fine, silky hair covering its body. Grub is pale white, fleshy, not hairy and two spots at the end of abdomen.

Host: Feed on all stored godowns foods, drug stores and a serious pest of tobacco.

Biology: Within grains and other stored materials, female lays approximately 50–80 eggs, which hatch into tiny white grubs after 8–10 days. There is a 6–10-day pupal period that follows the 4–5-week larval period.

The pupae that developed from the woven cocoons of the larvae emerge out as adult beetle. Adults is with short lifespan and are pale brown in color.

Nature of damage: The round, pinhead-sized holes on dry animal matter, coriander and turmeric is a sign of pest damage.

10.3 Methods for Detecting the Storage Pests:

10.3.1 Conventional Methods:

Conventional techniques like visual inspection, probe sampling, and insect trap method are popularly used. These techniques are time-consuming, labour-intensive methods but simple to follow.

A. Visual Detection:

Insect presence can be detected visually by regular monitoring. Visual detection is a uniform and qualitative method universally followed as a standard method. Presence of insect eggs, faecus, insect parts can be observed with the naked eye within the storage bags or grain lots

B. Probe Sampling:

It is a laborious and time-consuming method widely used for collecting samples. About 0.5-1 kg of samples were drawn using probes and visually inspected for the presence of insects or their body parts.

Different types of probes and traps are available in the market. UV light traps were also commonly used for detecting different insects like lesser grain borer, rice weevil, red flour beetle, saw toothed grain beetle in the warehouses (Mohan and Rajesh, 2016)

C. Visual Lures and Pheromones:

Incandescent, fluorescent and ultraviolet lights were used for detecting and monitoring storage pests. Most of the lures use lights with 280-600nm wavelength for effective luring. For some insects, sex pheromone and aggregation pheromone were used to attract the insects (Laopongsit and Srzednicki, 2010).

Insect density can be measured using Berlese funnel method and Uric acid method. For hidden infestation ninhydrin test is used especially for detecting rice weevil, angoumois grain moth and pulse beetle.

D. Modern Methods for Storage Pest Detection:

Modern tools like sensors, cameras, radiation, volatiles and accoustics are used for detecting both external and internal infestations at the initial stages in nondestructive manner. Electrically conductive mill is an instrument uses electric conductance as medium for differentiating infested and uninfested kernals.

In recent days, olfactory based detection techniques (Solid phase micro-extraction (SPME), X ray imaging and Electromagnetic spectrum-based imaging and sensor methods were gaining popularity (Gowda and Alagusundaram, 2013).

10.4 Management Practices for Stored Pests:

10.4.1 Preventive Measures:

As most of the insect pests are either active or passive flyers, preventive measures reduce the initial infestation and further buildup (Morales, 2002). Drying food products up to 10-14 % moisture, and proper storage in storage structures minimizes the pest infestation in warehouses.

A. Storage Structures:

Using bins and structures for storing food is an age-old practice for safe storage of domestic and commercial food supplies. In recent years, materials used for building structures are synthetized and conditions were automized to reduce the growth of insect pests (Manandhar *et al*., 2018). Storage structures are classified as (i) below and above ground or (ii) traditional and modern structures. Ancient humans dug pits and stored their grains which are mostly prone to the attack of rodents and other pests. With advancement in human knowledge, people started exploring different materials for construction. Earthen structures, brick bins, bamboo models, silos are some storage structures used commonly. In recent times, hermetic storage and low-pressure structures are popularly used.Low oxygen and elevated carbon dioxide levels are the basic principle in hermetic storage. Deoxygenated conditions increase insect mortality specially for pests like khapra beetle. But this kind of conditions also deteriorates the quality of grain storage. Technological advancement led to controlled aeration and gas alteration inside the storage structures and created additional advantages in storage.

B. Temperature:

Modifying temperatures can have a profound impact on insect growth and metabolism. The ideal temperature range for the majority of storage insects falls between 25 and 33ºC. Aeration and cooling emerge as crucial management techniques for effectively controlling insect infestations (Navarro and Noyes, 2001; Navarro, 2012). The direct heating or cooling of grains is a widely employed strategy against stored insect pests. Manipulation of temperature serves as a key tool in insect pest control during storage. Deviating from the optimal temperature range renders insects inactive, hindering their growth and leading to mortality. Extreme temperatures, whether hot or cold, can prove lethal to insects at various life stages. Implementing dry or wet heat in storage systems, as well as employing refrigerated aeration, has demonstrated effective outcomes, and high-frequency waves can also be utilized (Tyagi, 2012). Changing temperatures either low or high is a strategic approach to manage insect pests. Some pests thrive in moist and cool environments, while others favour hot and humid conditions. The majority of pests require temperatures exceeding 60–70°F to establish the damaging population. Consequently, sustaining a cooler temperature can mitigate excessive losses. In specific conditions, sustaining temperature between −4°C to 0°C proves fatal for many stored grain pests. Cold-sensitive species like *T. castaneum* and *Oryzaephilus mercator* are highly susceptible, whereas cold-tolerant species such as *Trogoderma* spp., *Plodia interpunctella* and *Ephestia* spp. can withstand lower temperatures. Although maintaining very high temperatures is an option, it comes with drawbacks such as the potential for grain cracking, hardening, and brittleness inside storage bins.

C. Modified Atmospheric Storage (MAS):

Insects rely on oxygen for their developmental metabolism. The Earth's atmospheric air consists predominantly of O_2 (21%), CO_2 (0.03%), and nitrogen (N_2) (78%). Adjusting the concentrations of these gases, in combination with fumigants such as phosphine, proves fatal for pests in stored grain (Constantin *et al.*, 2020).

This technique is known as modified or controlled atmospheric storage, involves artificially adjusting the gas composition within storage facilities while maintaining airtight conditions for an extended period (Wong-Corral *et al.,* 2013). Research indicates that exposing insects to decreased O_2 (<3%) and increased CO_2 (>50%) for over 24 hours causes significant distress and can lead to the mortality of residual populations (Tutuncu and Emekci, 2019). The concept of MAS revolves around manipulating the composition of storage gas with researchers studying the effects of elevated CO_2 and depleted O_2 on stored grain pests (Navarro, 2012). Notably, the importance of combinations involving reduced oxygen and elevated CO_2 levels (Cheng *et al.,* 2012) and high CO_2 pressure (Riudavets *et al.,* 2010) in management has been extensively documented.

Iturralde-García *et al.,* (2020) illustrated that an air mixture comprising 50% and 70% CO_2 proves lethal to both larval and pupal stages of *R. dominica* in packaged chickpeas, with LT_{50} ranging from 7 hours for larvae to 2 days for pupae. Top of Form However, the standardization of doses, treatment protocols, and the source of CO_2 supply pose challenges for large-scale treatments. Despite these concerns, the effectiveness of CO_2 suggests its potential integration with other fumigants in various proportions.

D. Ozone:

Ozone (O_3) is a highly reactive and powerful oxidizing agent widely employed in purification of water, food hygiene and deodorization (White *et al.,* 2010). Its ability to efficiently penetrate grain masses and rapidly decompose into O_2 without leaving residues makes it a compelling alternative fumigant for protecting stored grains (Pimentel *et al.,* 2009). Gaseous O_3 is produced artificially by utilizing air and electricity. Initially utilized in storage during the 1980s to eliminate insects and microflora, O_3 has proven effective in eradicating a diverse range of stored-grain pests (Isikber and Athanassiou, 2015; Subramanyam *et al.,* 2017). Sousa *et al.,* (2008) successfully employed O_3 to manage phosphine-resistant population of *T. castaneum, R. dominica*, and *O. surinamensis*. Despite its efficacy as a fumigant, a significant challenge in using ozone lies in achieving the appropriate dosage and ensuring continuous purging throughout the treatment duration. It is crucial to carefully select commodities for O_3 exposure, considering its strong oxidant properties.

E. Ionization Techniques:

Various ionizing radiations, like microwaves, X-rays, and gamma-rays (from sources like cobalt-60 and cesium-137) as well as electric beam, are employed in diverse forms to treat grains before storage for disinfection purposes (Hallman, 2013). This method has been widely utilized globally as a pest control and quarantine measure, aiming to achieve 100% mortality of insects in stored materials (Mohapatra *et al.,* 2015). Ionizing radiations exert their effects on the molecular level, causing damage to DNA structure of insects. This results in mortality, mutation and abnormality in the targeted pests. The radiations are known for their effective penetration capabilities and the ease of operation of irradiators. However, their application involves higher initial costs and dosage requirements, which can pose risks to human health. Even at lower doses, these radiations have the capability to sterilize or kill common grain pests.

F. Host Plant Resistance (HPR):

HPR is the plant ability to protect itself by deploying physical barriers that impede the feeding of storage insect pests (Kasozi, 2013). This resistance often relies on the interaction between plant species and specific characteristics, such as the presence of long, tight husk that reduce susceptibility to weevils and grain moths. Seeds with damaged or gaping husks tend to be more vulnerable to damage. Additionally, antibiosis in seeds, where certain plants contain chemical substance unacceptable to particular insect, plays a role in host plant resistance.

Physical and nutritional property of seed, such as a hard seed coat or vitreous endosperm, contribute to some resistance. Some plants exhibit specific oviposition preferences, which differ among seed species and varieties.

The thickness of grain coat and the hardness of the grain serve as barriers, impeding the maize weevil, *Sitophilus zeamais*, from penetrating the endosperm. Varieties with these characteristics have been proven to be less susceptible to infestation (Zakka *et al.,* 2013). Sorghum stored in granaries exhibits resistance to insect infestation, due to factors such as the existence of toxic alkaloid or amino acid, enzyme inhibitor, pericarp surface texture, insect feeding deterrent, grain hardness, grain temperature, and moisture content (Goftishu and Belete, 2014). Additional studies highlight grain hardness as a primary resistance parameter for *S. oryzae* in stored sorghum (Bamaiyi *et al.,* 2007).

10.4.2 Curative Measures:

A. Biological Methods:

Biological control stands out as an environmentally friendly strategy amid the phasing out of chemical pesticides, with ongoing efforts to develop novel biological methods. These approaches can be integrated into pest management practices to safeguard grains from insect damage. Biological control encompasses biotechnological interventions, as well as the use of parasitoids or predators to combat and prevent insect infestations (Scholler, 1997). In grain storages fungi and wasps, act as a biological vector, are used to target pulse beetles. A variety of parasitoid wasps, predatory beetles, bugs, and mites exhibit the capability to prey on multiple life stages of stored product insect pests, effectively subduing and consuming them (Abrol *et al.,* 1994). *Trichogramma* spp., in particular, show promise as bio agent on products by feeding on the egg stage of pests. Evaluations of this egg parasitoid have been conducted in various storage settings, including bulk wheat storage, bulk groundnut storage, bakeries, warehouses, and retail stores in Europe (Grieshop *et al.,* 2007). *Theocolax elegans*, is a parasitoid wasp, focuses on key grain pests with immature stages developing inside seed kernels. These pests encompass the lesser grain borer, weevils, drug store beetle, cowpea weevil and Angoumois grain moth (Flinn *et al.,* 2006).

Managing stored grain insect pests poses significant challenges due to the diverse species that can infest them. Research on the biological control of grains is still in its early stages. A primary limitation of this approach is its elevated cost, and maintaining cultures is crucial for achieving efficient insect pest control.

B. Botanical Control:

Botanicals are the chemicals produced by plants which possess insecticidal, repellent, antifeedant, and development inhibiting effects on storage insect pests. Several botanicals act as protectants against various stored grain insect pests (Shukla, 2007; Srinivasan, 2008). Plants like neem exhibit repellent, antifeedant, and feeding deterrent properties against storage insect pests. Extracts from plants, such as neem leaf powder, black pepper, turmeric powder, Sweet Flag Rhizome powder, among others, have proven effective in managing stored grain pests.

Notably, most of these botanicals lack residual effect, are available locally, and easily accessible to poor farmers (Saxena *et al.*, 2014). Neem and Pyrethrum, extensively studied, are commercially exploited for controlling storage pests (Dubey *et al.*, 2008). Plant extracts and essential oils can serve as fumigants, playing a crucial role in eliminating insect pests in stored grains due to their rapid degradation, low toxic effects, and local availability (Kerdchoechuen e*t al.*, 2010). The oil extracted from *Cymbopogon schoenanthus* (Poaceae) has been found to inhibit the growth and development of *C. maculatus* (Ketoh *et al.*, 2005). Botanicals exhibit such potent action effects that they can impede the development of eggs and other immature stages located within the grain kernels.

C. Biopesticides:

Utilizing biological control for stored grain protection is a promising technique that avoids harming environmental health. Commercially available entomopathogenic fungi commonly used against field crop pests, including *Beauveria bassiana* and *Metarhizium anisopliae*, as well as the *Bacillus thuringiensis* (Bt), have been evaluated extensively against stored-grain pests, particularly beetles. *Bacillus thuringiensis var. kurstaki* (Btk) has been reported as effective in managing stored grain pests, specifically *P. interpunctella* and other moths (Shapiro-Ilan *et al.*, 2007; Lord *et al.*, 2007). Entomopathogens, particularly fungi, recorded population reductions compared to conventional insecticides, the process is slower and less efficient. However, their use in storage conditions is considered promising. The application of entomopathogenic fungi in stored pest management has been highlighted by Rumbos and Athanassiou (2017). Additionally, viruses, mainly baculoviruses, have been extensively studied, particularly in lepidopteran pests, *P. interpunctella* and *E. cautella* (Vail *et al.*, 1991). These biological control methods offer an environmentally friendly approach to stored grain protection, even though their efficacy may be slower compared to conventional insecticides.

D. **Pheromonal Approach:**

Pheromones are ectohormones released by either male or female partners to influence each other's behavior, are now commercially available for approximately 20 species of stored grain pests (Phillips & Throne, 2010). These are commonly employed for pests like *P. interpunctella*, *Lasioderma serricorne, T. castaneum, T. confusum* and *Trogoderma variabile* these pheromones are strategically positioned within suitable traps to ensure smooth release, maximum attraction, and effective trapping processes. The proper placement of pheromone-baited sticky traps in buildings, granaries, and other flat landing sites is essential for the efficacy of the utilized pheromones (Nansen *et al.,* 2004). This approach serves as an effective and environmentally friendly method for monitoring and managing stored grain pests by disrupting their mating and reproductive behaviors.

E. Chemical Methods:

Chemical methods are commonly employed to control infestations of stored grain insect pests, with the application of chemical insecticides aimed at preventing or suppressing such infestations. Chemical treatments typically involve the use of fumigants and contact insecticides during the storage period. Before utilization, storage rooms must undergo disinfection using approved residual insecticides, a critical step in managing stored pests. It is important to emphasize that synthetic insecticides are not advisable for food grains intended for consumption. Only chemicals registered for direct application to grains should be employed, following recommended doses.

Fumigants like phosphine, cyanogens, ethyl formate, sulfuryl fluoride, and carbonyl sulfide, are highly effective in rapidly killing all stages of stored product insects (Mohapatra *et al.,* 2015). Methyl bromide and phosphine are commonly used chemicals for fumigation. Phosphine fumigation, in particular, is widely employed as a control measure for insect pests during storage, proving more effective than treated bags (Demissie, 2006). Nitric oxide (NO) is a recently identified fumigant that exhibits significant potential for the control of stored grain pests, serving as an alternative to methyl bromide, particularly in areas where the use of the latter has been discontinued.

In India, phosphine is the predominant fumigation option as methyl bromide has been phased out. Aluminium phosphide, recommended for cover and shed fumigation, is widely used, with precipitate silica emerging as a new method against stored pests (Saha *et al.,* 2021).

It is crucial to avoid directly spraying insecticides on food grains. Instead, treatment should be directed at wall, dunnage, ceilings of empty godowns, bags, alleyways, and gangways. Ampoules of ethylene dibromide (EDB) should be used at specified doses depending on the type of grain. Phosphine, while highly effective, raises human safety concerns due to its poisonous nature and potential adsorption in grains during fumigation.

F. Nano Technology:

Nanotechnology is gaining prominence in both basic and applied scientific fields, particularly in the realm of stored-grain protection. Nanoparticles derive their significance from distinctive properties, encompassing modifications in electrical conductivity, surface chemistry, and reactivity (Zayed, 2018). Commonly, metallic oxides like zinc, silver, aluminum, and silica are synthesized as nanoparticles (Stadler *et al.,* 2010). Notably, zinc oxide nanoparticles are extensively employed due to their antibacterial, antifungal, UV filtration, enhanced catalytic, and photochemical activities (Meruvu *et al.,* 2011). Malaikozhundan *et al.,* (2017) synthesized and developed zinc oxide nanoparticles coated with *Bacillus thuringiensis* (Bt-ZnO NPs) to combat C. maculatus, noting a decrease in fecundity and hatchability (LC50 - 10.71µg/mL) along with extended larval, pupal, and total development periods (@ 25µg/mL). In a study by Rahman *et al.*, (2020), nickel-oxide nanoparticles (NiO NPs) were examined against C. maculatus infesting black gram, resulting in reduced fecundity and prolonged developmental periods. Efficacy assessments of nanoparticles were also conducted against *T. castaneum*, *S. oryzae*, *R. dominica* and *C. maculatus*, revealing noteworthy impacts on adult insect mortality, fecundity, hatchability, and biology in laboratory conditions (El-Saadony *et al.*, 2020). Additionally, Ahmed *et al.*, (2021) proposed the nanoencapsulation of a 25 kDa cysteine protease derived from *Albizia procera* (ApCp) as a promising eco-friendly approach for insect pest control. Despite these promising findings, detailed field-level studies on nanoparticle applications are essential to fully harness this novel approach. The potential of nanotechnology in stored-grain protection opens up innovative possibilities for effective and environmentally friendly pest control methods.

G. Molecular Techniques:

The disruption of normal gene expression in organisms is a cutting-edge approach to insect management, involving molecular tools: RNA interference (RNAi) and Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) (Perkin *et al.*, 2016). The *Tribolium castaneum*, has been widely studied as a model insect for these techniques, with available data focusing on this species (Gilles *et al.*, 2015). *T. castaneum* is chosen as a preferred host due to its easy multiplication in lab conditions and good RNAi response across all developmental stages. In this context, RNAi act on double-stranded RNA (dsRNA), while CRISPR deactivate Cas9 (DNA binder), thereby inhibiting further gene expressions (Qi *et al.*, 2014). These techniques hold potential for effective use in stored-grain pest management, but extensive research is needed to harness their capabilities fully. This novel technology, along with similar techniques such as gene editing and gene modifications, present a futuristic approach to insect management in stored products.

10.5 Integrated Pest Management:

Integrated Pest Management (IPM) is comprehensive approach that incorporates various components to efficiently manage insect pests in stored grains. It relies on a combination of strategies, including botanical controls, biological controls, HPR, physical controls, and chemical controls, to effectively manage insect populations and maintain ecological balance. This multi-faceted approach aims to reduce the reliance on any single control method and considers the environmental impact of pest management practices (Mboya, 2011). By integrating different strategies, IPM seeks to minimize the use of chemical pesticides and promote sustainable and environmentally friendly methods for stored grain protection.

10.6 Conclusion:

In conclusion, the safe handling and protecting stored product, particularly grains, are critical areas of research for Post-Harvest Engineers and Entomologists. The growing concern for food security and safety has prompted advances in various fields, leading to the development of modern and integrated pest management (IPM) strategies. The ongoing efforts in advancing IPM strategies underscore the significance of a multi-faceted approach to minimize losses throughout the grain supply chain. The specific challenges faced by developing countries, exemplified by Ethiopia and India, emphasize the critical need for continuous research and application of effective pest management methods. By integrating physical, biological, botanical, chemical, and host plant resistance approaches, coupled with a strong emphasis on IPM, these regions can work towards mitigating losses, preserving economic value, and ensuring the nutritional quality of stored grains. The urgency to strengthen research efforts, particularly in developing countries, underscores the importance of proactive measures to secure sustainable and sufficient food supplies in the face of persistent insect infestations.

10.7 Reference:

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