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21. Management of Stored Grain Pest: Ancient Era to Modern Era

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Abstract:

Food safety and security are critical global concerns, proper management of storage pests is crucial for minimizing economic losses and health risks, especially in agriculture-centric economies like India, where poor pest control can disrupt supply chains and affect both consumer prices and public health. Historically, pest management evolved from ancient practices using natural remedies and physical barriers, such as rice flour and clay, during medieval improvements like enhanced storage facilities and traditional methods with common salt and Azadirachta indica leaves. The Early Modern Era introduced chemical innovations, including fumigants and insecticides, alongside the emergence of stored-product entomology and biological controls. The 20th Century saw the adoption of synthetic chemicals and Integrated Pest Management (IPM) strategies, combining multiple control methods. In the 21st Century, modern pest management focuses on advanced technologies such as nanotechnology and Insect Growth Regulators (IGRs), alongside enhanced policies, regulations and public education. Future strategies are likely to integrate these technologies with robust policy frameworks to improve food safety and security globally.

Keywords:

Integrated Pest Management, Nanotechnology and Storage Pests.

21.1 Introduction:

Food safety and security have emerged as critical global issues, with the preservation and safe storage of food grains being essential for ensuring their timely delivery to consumers. Various food commodities, including harvested cereals, legumes and semi-perishables, require secure storage solutions to be effectively utilized at both domestic and commercial levels (Said and Pradhan, 2014). The majority of storage infrastructure is geared towards grains, ranging from small metal bins to large grain elevators or silos. However, stored agricultural commodities are susceptible to contamination and damage from biotic and abiotic factors during extended storage periods. Biotic agents, such as insects, mites, rodents, birds and microorganisms, contribute significantly to storage losses, with insects alone responsible for about 10 to 20% of total losses (Esther *et al.,* 2014).

Over 600 beetle species, 70 moth species, and 355 mite species are known to cause damage to stored products of both agricultural and animal origins. The presence of these pests results in considerable quantitative and qualitative losses. Insect pests often migrate from fields and establish themselves in storage environments due to favorable microclimatic conditions, and their populations can be sustained throughout various processing and storage stages (Hagstrum and Phillips, 2017). Infestations frequently start during the crop ripening stage and persist through storage (Sallam, 1999). Additionally, old storage bags, structures, containers, and cross-contaminations from harvesters and machinery are significant sources of infestations (Perez-Mendoza *et al.,* 2004; Sinclair and White, 1980). To mitigate initial infestations, it is crucial to harvest and dry grains to an appropriate moisture level, as recommended by grain storage agencies. Furthermore, the spread of stored product insects can occur through grain movement between regions or through active flight, as many insect species are proficient fliers (Ridley *et al.,* 2011).

Storage pest management is a vital aspect of post-harvest agriculture, involving the implementation of strategies and techniques to protect stored agricultural products from pests such as insects, rodents, and fungi. In India, where agriculture is a cornerstone of the economy and a key source of livelihood for millions, managing these pests effectively is of paramount importance. This field is crucial not only for ensuring food security but also for preserving the quality and nutritional integrity of stored goods. The impact of storage pests is significant, with estimates indicating that around 10-30% of agricultural produce is lost due to pest infestations during storage, underscoring the seriousness of the problem (Singh *et al.,* 2021).

This loss is especially significant in India, where ensuring food security remains a persistent challenge. The evolution of storage pest management in India reflects its agricultural history. Traditionally, methods such as using natural repellents like neem leaves and turmeric were common for centuries. However, the Green Revolution of the 1960s ushered in a major shift toward chemical pest control, introducing synthetic pesticides that transformed pest management practices. While these chemicals proved effective, their negative environmental and health impacts became increasingly evident over time, prompting a gradual transition toward more integrated and sustainable pest management approaches (Moore *et al.,* 2004; Bezabih *et al.,* 2022).

21.2 Importance of Storage Pest Management:

In India, managing storage pests has major economic consequences. Since agriculture plays a key role in the country's GDP, losses from storage pests directly affect farmers' earnings and the overall economy. Midega (2016) reported that poor pest management in storage results in significant financial losses, especially for small and marginal farmers. This not only reduces the availability of marketable surplus but also disrupts the entire supply chain from farmers to consumers. Consequently, this impacts farmers' incomes and raises food prices, affecting consumer affordability. Furthermore, managing storage pests is crucial for public health in India, as pests like rodents and insects can spread diseases and contaminate stored food, making it unsafe to eat. Consuming pest-infested food can lead to serious health problems, including allergic reactions, food poisoning, and exposure to harmful substances produced by certain fungi (Obeng-Ofori, 2007).

The incorrect application of chemical pesticides in storage areas has sparked concerns about residual toxicity and the possible long-term health hazards. This situation emphasizes the importance of adopting effective, safe and sustainable pest management strategies to safeguard the health and well-being of the population.

Managing stored grain pests has been a crucial aspect of agriculture and food security throughout history. The approach to pest control has evolved significantly from ancient times to the modern era. Here’s a brief overview of how these practices have developed.

21.3 Ancient Era:

21.3.1 Ancient methods of pest control practices:

The negative impacts of synthetic pesticides are increasing daily. Pest issues remain ongoing and human tragedies periodically occur across various regions of the country. Historically, farmers used a range of plant-based products for crop protection and nourishment. These included crop residues such as shells and ash, animal products like cow urine, cow dung and milk, as well as minerals such as red earth and sand. Many of these materials, which are safe, biodegradable and locally available, are now receiving renewed attention (Shaila and Begum, 2021). Traditional methods involving these products were carefully designed and still hold practical value today. Some well-known plant species (Table 21.1) used during Vedic times is listed by Narayanasamy (2002).

Table 21.1: Pest control plants of Vedic era

Sr. No	Common name	Scientific name
1	Asoka	*Saraca asoca*
2	Aswatha	*Ficusr eligiosa*
3	Kkadasingi	*Gynandropis pentaphylla*
4	Maharksha (Vijra)	*Euphorbia tirucalli*
5	Neem	*Azadirachta indica*
6	Nyagrotha	*Ficus indica*
7	Palasa	*Butea frondosa*
8	Stapuspa	*Stapuspa*
9	Sikhandi (Juha)	*Jasminum auriculatum*
10	Vidanga	*Embelia ribes*

21.4 Medieval Period:

21.4.1 Improved Storage Facilities:

Improved seed storage facilities are essential for preserving seed viability and vigor, marking a significant advancement from traditional methods. Historically, seed storage in regions such as India utilized a variety of structures, including bamboo baskets, mud pots and wooden boxes. For instance, the Kanaja, a cylindrical bamboo container plastered with a mixture of mud and cow dung, was prevalent in paddy-growing regions, while the Sandaka, a wooden box with legs and partitions, was used by households to store pulses and grains (Shobhanagnur *et al.*, 2006). Other traditional storage solutions include the Kothi, a large room designed for substantial quantities of grains, and the Utrani, a series of clay pots stacked vertically for smaller quantities (Shobhanagnur *et al.*, 2006). Innovations have led to the development of structures like the Crib, which is an elevated, well-ventilated storage unit designed to enhance airflow and drying, though it provides limited protection against pests (Adesina *et al.*, 2019). The Bamboo House, a more modern variant of traditional storage, utilizes tightly fitted bamboo walls and coatings of cow dung or urine to protect against insects and rodents, while the Obeh, an airtight bamboo storage platform, is specifically used for unthreshed rice (Karthikeyan *et al.*, 2009). Additionally, gunny bags treated with neem kernel extract represent a contemporary solution that balances durability, ease of handling, and pest control, allowing for effective storage of seeds while facilitating air circulation (Adesina *et al.*, 2019). These advancements illustrate a significant evolution from traditional methods to more sophisticated and efficient storage solutions, enhancing the preservation and longevity of stored seeds.

21.4.2 Traditional practices:

Traditional practices for grain storage include keeping red gram (*Cajanus cajan*) grains with common salt, which are then placed in jute gunny bags for storage. This method provides protection from insects for 6 to 8 months. *Azadirachta indica* leaves are frequently used in traditional storage methods throughout India. Lime and camphor are also commonly used for storing paddy in gunny bags. Additionally, neem (*Azadirachta indica*) oil is used for treating seeds, with 20 ml of oil mixed with 1 kg of pulse seeds and neem seed kernel extract is used to treat jute gunny bags before storage. Storing grains with sweet flag (*Acorus calamus*) powder can prevent insect infestation for up to 6 months, as the strong odor of sweet flag acts as a repellent against storage pests (Karthikeyan *et al.*, 2009; Kale *et al.*, 2021).

To protect stored grains from insects, farmers often rely on various forms of traditional knowledge. Around the world, specific storage techniques have been developed to maintain the quality and quantity of food until consumption or transport. Farmers have created numerous traditional storage structures using locally available materials such as bamboo, straw, wooden planks, mud, bricks and cow dung. Plant components and extracts are also commonly used as natural pesticides (Suleiman and Rugumamu, 2017).

21.5 Early Modern Era (16th -19th Century):

21.5.1 Pheromones:

In 1898 entry of American Miller column, Johnson described the mating posture of the *Ephestia kuehniella* female, noting that the abdomen protruded between wings. Norris & Richards in 1933 and Dickins in 1936 discovered that males were attracted to the pheromones released by calling females. Changes in male flight behavior when approaching a calling female pyralid moth have also been documented (Mankin and Hagstrum, 1995).

The sex pheromone of the black carpet beetle, *Attagenus unicolor*, was identified in 1966 (Silverstein *et al.*, 1967) and was among the first insect pheromones to be identified and synthesized. Subsequently, a common pheromone found in several species of pyralid moths was identified (Brady *et al.*, 1971). By the mid-1980s, commercial pheromone traps and lures for stored-product insects became available (Phillips *et al.*, 2000). Today, pheromone traps are used globally to detect and monitor populations of key pest species as part of routine pest control and Integrated Pest Management (IPM) programs (Campbell *et al.*, 2012; Toews and Nansen, 2012; Hagstrum and Phillips, 2017). An expanding use of pheromones in stored-product IPM includes government-approved, commercially available pheromones for controlling pest moth populations through mating disruption, mass trapping and various attract-and-kill methods, as reviewed by Savoldelli & Trematerra (2011).

21.5.2 Biological Control:

Natural predators of insects are well-documented for most stored-product pests. Hagstrum & Subramanyam (2009) identified 468 species of natural enemies and research into biological control has been ongoing for over a century. For instance, Froggat (1912) found that the ichneumonid wasp *Venturia canescens* (Gravenhorst) effectively managed *E. kuehniella* in a flour mill. A study on biocontrol indicates that among 13 species of natural enemies targeting 19 types of stored-product pests, 163 out of 212 estimates of pest mortality showed rates between 70% and 100%, with over half falling between 90% and 100% (Hagstrum and Subramanyam, 2006). Releasing *Theocolax elegans* (Westwood) in stored wheat achieved a 95% reduction in *Rhyzopertha dominica* (Flinn *et al.*, 1996) and decreased the presence of insect fragments in the milled flour (Flinn and Hagstrum, 2001). A private company specializing in the sale of parasitoids for the European organic food market, including individual consumers has seen success (Flinn and Scholler, 2012) and several large commercial insectaries in North America produce parasitoids and predators for large-scale release in stored-product environments. An example of effective large-scale biological control for stored grain is the inoculative release of a predator against *Prostephanus truncatus* in Benin (Borgemeister *et al.*, 1997).

21.5.3 Chemical Innovations:

Fumigants and residual insecticides were introduced in the late 19^{th} and early 20^{th} centuries and the regulation of pesticides has a long history (Deck, 1975). Fumigants are gaseous pesticides that effectively eliminate infestations with minimal to no detectable chemical residue. Carbon disulfide was first used in 1854 but was not applied to grain until 1879. Hydrocyanic acid came into use in 1886, chloropicrin in 1907, ethylene oxide in 1927, and methyl bromide (initially as a fire extinguisher) in 1932 (Arthur and Rogers, 2003; Simmons and Ellington, 1936). Phosphine, used in Germany for many years, eventually became the predominant fumigant worldwide. To ensure even distribution of fumigants in large grain bins, methods like recirculation or closed-loop fumigation were developed in Europe in the early 1900s and have been used more recently in the United States (Jones *et al.*, 2011; Lindgren and Vincent, 1962). With the recent ban on methyl bromide due to its ozone-depleting effects and the development of insect resistance to phosphine, research has shifted towards sulfuryl fluoride as an alternative (Nayak *et al.*, 2015.).

In 1936, it was recommended to use spot or local fumigation of equipment between full mill fumigations (Dean, 1936). Early fumigants did not penetrate food residues well, so equipment had to be cleaned and sealed before fumigation. However, insects from untreated equipment often reinfested treated equipment. As more effective fumigants became available, cleaning times were reduced and the practice of fumigating all equipment simultaneously improved the effectiveness of spot fumigation. In some cases, spot fumigation has replaced full mill fumigation. In-transit fumigation, developed to address insect infestations found during the loading of railcars and ships (Davis and Barrett, 1986), has been further facilitated by the use of shipping containers (Graver and Banks, 2008).

21.6. 20th Century:

21.6.1 Synthetic chemicals or Low-Risk Chemicals:

The use of residual insecticides has progressed from low-risk natural pyrethrum to synthetic neurotoxins that can be potentially hazardous. Nowadays, safer alternatives like juvenile hormone analogs, diatomaceous earth, and spinosyns are commonly used. Products such as methoprene, hydroprene, pyriproxyfen, chlorfenapyr and diatomaceous earth are commercially available and spinosad has been developed and registered for use on grain (Arthur 2012; Mondal and Parween, 2000). Recent research has examined the effectiveness of additional insect growth regulators like novaluron, a newer spinosyn called spinetoram, and neonicotinoids such as imidacloprid and thiamethoxam as residual insecticides for stored products (Kostyukovsky and Trostanetsky, 2006; Saglam, 2013). Consequently, there is a range of effective, low-risk chemical products available for stored-product applications and their use is expected to expand in the near future.

21.6.2 Integrated Pest Management (IPM):

Pest management, including postharvest infestations, is now most effectively and widely managed through Integrated Pest Management (IPM). The IPM approach is effective in preventing resistance by focusing on a balanced use of non-chemical methods (such as botanicals, light traps and natural predators) alongside selective synthetic treatments (Obeng, 2007). IPM involves the strategic use of available resources both natural and synthetic, to manage pests without disrupting ecological balance. Overreliance on synthetic pesticides should be avoided and they can be used in conjunction with botanicals as part of IPM. Combining botanicals with emamectin benzoate effectively controls storage insects and improves seed quality. Insecticidal plant extracts, which have broad-spectrum activity and are easy to prepare from local materials, are noted for their effectiveness. Neem-based products like Neem Azal and neem seed oil (NSO) effective against *S. zeamais*, and Azadirachtin has been shown to cause 100% mortality in *Sitophilus oryzae*. A list of important botanicals for controlling various storage pests such as *Sitophilus oryzae*, *S. zeamais* and *Callosobruchus chinensis*. Botanicals break down into harmless metabolites quickly, do not contribute to pest resistance and are less harmful to beneficial organisms. Therefore, different botanicals can be effectively used for treating grains, with their efficacy varying by location and storage conditions.

Integrated Pest Management (IPM) is expected to become a key strategy for managing storage pests in India in the future. IPM is a comprehensive approach that combines multiple pest control methods such as cultural, mechanical, biological and chemical, to minimize risks to both human health and the environment. The adoption of IPM is on the rise in India, driven by the need for more sustainable and environmentally friendly pest control solutions. Moving forward, IPM in India will not only integrate existing pest control techniques but will also embrace new technologies and innovations (Chakravarthy, 2020). Numerous successful case studies from India highlight the benefits of IPM in managing storage pests, such as significant reductions in pest populations and decreased reliance on chemical pesticides, particularly in the storage of wheat and rice. These successes often involve active community engagement and the education of farmers and storage managers on IPM practices. Promoting these success stories is vital for encouraging wider adoption of IPM strategies throughout India (Mishra *et al.*, 2024).

21.7 Modern Era (21st Century)

21.7.1 Nanotechnology in stored-grain protection:

Nanotechnology is increasingly being explored in both basic and applied sciences, including for the protection of stored grains. The importance of nanoparticles has grown due to their unique properties, such as altered electrical conductivity, surface chemistry and reactivity. Various metallic oxides, including zinc, silver, aluminum and silica, are commonly used in nanoparticle. Among them zinc oxide nanoparticles are particularly notable for their antibacterial, antifungal, UV filtration, high catalytic and photochemical activities. Bt-coated zinc oxide nanoparticles (Bt-ZnO NPs) for controlling *Callosobruchus maculatus* and reported reduced fecundity and hatchability (LC50 - 10.71 µg/mL), along with extended larval, pupal and overall development periods at a concentration of 25 µg/mL. The entomotoxicity of surface-functionalized silica nanoparticles (SNP) against *Sitophilus oryzae* and observed over 90% mortality. Nickel oxide nanoparticles (NiO NPs) on *C. maculatus* infesting black gram and found decreased fecundity and extended developmental periods at doses of 5, 10, 20, and 40 ppm NiO NPs. Efficacy studies of nanoparticles have also been conducted against *Tribolium castaneum, S. oryzae, Rhizopertha dominica* and *C. maculatus*, showing significant effects on adult mortality, fecundity, hatchability and overall biology under laboratory conditions (Guru *et al.*, 2022).

21.7.2 Insect Growth Regulators (IGRs):

Insect hormones and their analogues, known as insect growth regulators (IGRs), are employed to manage insect populations. These IGRs have shown to be particularly effective against various stored-product moths and beetles when used in confined spaces. They work by disrupting reproductive processes in insects, particularly affecting egg-laying behaviors. For example, IGRs like methoprene and hydropene are used to prevent pupation in *Tribolium castaneum* and *Tribolium confusum*. Methoprene can also inhibit *Oryzaephilus mercator* and *O. surinamensis* at a concentration of 1 mg/kg, while hydropene completely inhibits the development of adult progeny in *Sitophilus granarius* at doses of 10-20 mg/kg. For improved efficacy, IGRs might be more effective when incorporated into attractant-impregnated baits rather than being applied directly to food.

21.7.3 Policy and Regulatory Developments:

The future of storage pest management in India will be significantly influenced by global regulations and policies. International agreements and standards, such as those established by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO), play a crucial role in shaping pest management approaches. These regulations typically emphasize the safe application of pesticides, the promotion of sustainable practices, and the safeguarding of food safety and security. India, as a participant in the global community, is guided by these international regulations, which are reflected in its own policies and guidelines for storage pest management. In the future, international cooperation and adherence to global standards are expected to become increasingly important for India's storage pest management efforts. Collaborative research, information exchange and capacity building will be essential in advancing pest management strategies. Furthermore, meeting international standards will help ensure that Indian agricultural products fulfill global market requirements, which is vital for the country’s export-focused industries. Aligning India's pest management practices with international standards will also enable the exchange of best practices and technologies, thereby enhancing the country’s pest management effectiveness.

21.7.4 Public Awareness and Education:

In India, implementing innovative pest management strategies encounters several challenges. A major issue is the lack of awareness and education among farmers about advanced pest management techniques. Many small-scale farmers continue to rely on traditional methods or excessive chemical pesticide use, often due to limited access to information or training. Financial limitations and restricted access to new technologies also present significant obstacles. Moreover, India’s varied climatic conditions and crop types require region-specific strategies, making it difficult to apply a uniform pest management approach. To address these challenges, several adaptive strategies and solutions are being pursued. Government initiatives and public-private partnerships are crucial in educating farmers and encouraging the adoption of modern pest management practices. For example, the Indian government’s “Pradhan Mantri Krishi Sinchayee Yojana” scheme promotes micro-irrigation and water management practices, which indirectly help control pest populations by creating less favorable conditions for their growth. Establishing local farmer groups and cooperatives aids in the dissemination of knowledge and collective adoption of new practices. Research institutions in India are increasingly focusing on developing cost-effective and practical pest management solutions tailored to local conditions. For instance, the Indian Council of Agricultural Research (ICAR) conducts research and extension activities related to integrated pest management (IPM) and sustainable agriculture practices. Emphasizing participatory research ensures that the solutions are both practical and acceptable to the farming community.

21.8 Perspectives for the Future:

Managing Bruchid pests has been essential since ancient times. Stored grain pulses used to remain safe for several years. Although various synthetic pesticides have been used against bruchid pests, many of these chemicals have harmful effects.

Some methods come with drawbacks such as affecting non-target species, causing resistance, or contributing to pollution. Despite these issues, plant botanicals offer a promising alternative. They are cost-effective, readily available, environmentally friendly and safe for human health, making them useful for managing pests like *C. maculatus* in stored grains. For farmers, protecting pulses from pest infestation is crucial. Combining several methods, ranging from inexpensive traditional techniques to advanced botanical, ergonomic and microbiological practices can provide a comprehensive integrated pest control strategy.

21.9 A Vision for Stored-Product Insect Pest Management:

The UN Food and Agriculture Organization predict that the global population will reach 9.8 billion by 2050, a 70% increase from the 5.6 billion estimated in 1995. The required food production will vary by region: industrialized countries will need to maintain current production levels, while developing countries will need to increase production two- to five-fold. To meet these demands, enhanced crop production must include robust postharvest security. Investing public resources in IPM research for stored products will be crucial to safeguarding the global food supply. While significant research has been conducted on IPM components, further study is needed on how to integrate, streamline, and optimize these components. Determining the best timing for IPM interventions is also essential. Ultimately, IPM strategies for stored products will only be adopted if they prove cost-effective, so further research into the economic aspects of pest management is necessary.

21.10 Conclusion:

The journey of food grain storage and pest management reflects the evolving landscape of agricultural practices, highlighting the critical interplay between technology and traditional methods. As global concerns over food safety and security intensify, effective pest management remains vital to ensure the quality and availability of essential food supplies. With historical practices laying the groundwork, modern advancements ranging from innovative technologies to Integrated Pest Management (IPM) offer promising pathways to mitigate economic losses and health risks. Looking ahead, the integration of cutting-edge solutions with strong policy frameworks and public education will be crucial in addressing the challenges posed by pests, ultimately enhancing food security for future generations. By prioritizing these strategies, we can build a resilient food system that safeguards health and supports sustainable agricultural practices worldwide.

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