

Innovative approaches for the detection and management of stored-grain insect pests

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Abstract

Stored-grain insect pests cause critical global post-harvest losses, with an estimated 17% of food lost during storage at an annual cost of \$100 billion, including 14 million tonnes in India. Infestations by beetles, weevils, moths and borers lead to both quantitative damage and qualitative degradation, altering essential nutrients and organoleptic properties. Rapid early detection technologies including olfactory perception systems (SPME and E-noses) and electromagnetic spectrum techniques (computer vision, hyperspectral imaging and X-ray imaging) enable prompt identification even at low pest densities. To mitigate these losses, innovative management strategies combine hermetic and low-pressure storage structures with physical non-thermal treatments such as cold plasma, ozone and irradiation. Furthermore, sustainable protection is achieved by integrating biorational tools (essential oils and insect growth regulators) alongside advanced molecular approaches like RNA interference (RNAi) and CRISPR-Cas across the post-harvest chain.

Keywords: Stored-grain insect pests, post-harvest losses, grain storage, early pest detection, electronic nose (E-Nose), spme, computer vision

Introduction

As the global population continues to expand, maintaining robust grain storage systems has become a fundamental pillar of food security. With approximately 80% of all food of plant origin derived from cereals and legumes, the pressure to meet growing food demands is immense. However, a significant portion of this production never reaches the consumer; an estimated 17% of global food production is lost during the storage phase (Bouchelos, 2018) ^[13]. These pest-driven losses represent a massive economic burden, costing the global economy approximately \$100 billion annually. In India alone, storage losses reach roughly 14 million tonnes, valued at ₹7,000 crore each year (Bisheko *et al.*, 2023) ^[12]. Beyond the sheer reduction in quantity, insect infestations cause severe qualitative degradation, including the loss of vital nutrients like amino acids, proteins, and fats, alongside undesirable organoleptic changes in taste, odour, and texture. Consequently, bridging the gap with timely detection and innovative management approaches is no longer optional but essential to protect grain quality and secure a sustainable food future.

What are Stored-grain insect pests?

Stored grains are susceptible to infestation of various pests like insects such as borers and beetles, fungus such as *Aspergillus* and various mites. Of these, the insect pests account for 10% of storage loss. These are insects that infest and cause damage to stored grains and grain products which leads to both quantitative as well as qualitative losses. These include various beetles, weevils, moths and borers *etc.*

Classification of stored grain insect-pests

Stored-grain insect pests are classified based on feeding habits and feeding behaviour. Based on the feeding habits stored-grain insect pests are divided into-

- **Primary pests:** insects which attack whole and sound grains.
- **Secondary pests:** Insects which feed on broken or damaged grains.

Based on the feeding behaviour these are further classified as-

- **Internal feeders:** such insects complete their life stages and meanwhile also feed inside the kernels.
- **External feeders:** insects that feed on the outer surface of grains

Innovative Approaches in Pest Detection

Stored grains are susceptible to various pests due to many factors like improper moisture levels, improper storage conditions, lack of inspection. Thus, it becomes highly important to detect these pests and prevent it from damaging the seeds. Various different methods for this have been practised since a long time which includes visual inspection, probes, lures and pheromones, Berlese funnel method and uric acid method. These methods are effective but either take a lot of time or do not give precise observation thus, creating a demand for alternate approaches.

Innovative approaches for stored grain pest detection offers an easy, quick solution for detection even at low density. These techniques involve use of sensors, cameras, radiation sources, sound *etc.* to detect the infestation. These technologies can be categorized according to the characteristics used for insect detection, such as acoustic signals, electrical conductivity, olfactory perception, and responsiveness to electromagnetic spectrum.

1. Olfactory Based

Solid Phase Micro Extraction (SPME)

Odour detection for insect infestation has gained popularity because of various advantages like early detection, high sensitivity and easy to operate (Pillonel *et al.*, 2002) ^[44]. SPME involves isolation of volatile compounds vapourised from grain samples and evaluation by Gas Chromatography-Mass Spectrometry (GC-MS) following condensation (Banga *et al.*, 2018) ^[9]. Laopongsit *et al.* (2014) ^[34] carried out the preliminary study of SPME for detecting infestation of insects like *T. castaneum*, *R. dominica*, *S. oryzae* and *C. pusillus* in wheat grains due to detection of aggregation pheromone of each species.

Electronic Nose

An electronic nose detects volatile compounds produced by contaminants beyond the capacity of human nose. It comprises electronic sensors like metal Oxide Semiconductor (MOS), electrochemical, optical and quartz crystal microbalance and pattern recognition software (Banga *et al.*, 2018) ^[9]. These detect the volatile compounds released from the stored food grains and responds by changing their electrical properties. Few of the commercially available e-noses are PEN2, PEN3 & FOX3000. Hou *et al.* (2025) used e-nose to detect *Tribolium castaneum* in wheat grains.

2. Electromagnetic Spectrum Based

2.1 Imaging

a. Machine Vision within Visible Domain

Machine vision is also popularly known as computer vision uses the principle of object recognition and classification on the basis of information extracted from images captured by using a camera (Sun, 2016) ^[52]. It is a non-destructive technique which gives rapid and accurate results. It has three main processes viz. image acquisition, image processing or analysis and recognition and interpretation. The technique has various uses like monitoring and evaluation of varieties and soundness of grains, amount of foreign material, mold and insect infestation *etc.* in bulk grains can be successfully carried out (Aviara *et al.*, 2016) ^[7]. Zhu *et al.* (2022) ^[57] used a YOLO-based model for detecting stored grain pests in wheat, corn and paddy. Yan *et al.* (2026) studied hyperspectral imaging system for separating healthy and *Sitophilus oryzae* infested wheat samples.

b. X-ray Imaging

X-ray imaging is a fast and non-destructive method, used for detection of insect infestation inside the kernels of grains in stored grains (Karunkaran *et al.*, 2003). This method uses X-rays which are electromagnetic radiations having wavelength of 0.01 to 10 nm. Along with providing clear view of the internal structure of grains, this method also allows detection of both live and dead insects (Rajendran, 2005) ^[46]. Nawrocka *et al.* (2012) ^[42] detected loss in wheat kernels infected by granary weevil using soft x-ray imaging. Despite the advantages, requirement of costly machine to generate the x-rays, films for exposure/automatic computer-enabled software system, and an expert to interpret the radiographs remains a challenge.

c. Thermal Imaging

It is a night vision technology, which improves the visibility of an object in a dark environment by detecting the infrared

radiation energy emitted by the object and transforming it into the visible image. This image is known as thermogram (Nanje Gowda and Alagusundaram, 2013) ^[41] which is a result of various detectors and lenses, thermal imaging cameras and data collection tools. This technique detects damaged grains, foreign materials as well as internal and external grain infestations. Chelladurai *et al.*, (2012) have reported a detection accuracy of around 80% in moong beans infested by *C. macuatus* by using this technique. Ibrahim *et al.* (2019) ^[29] studied the thermal detection of various stored grains like *Sitophilus oryzae*, *Bruchidius incarnatus* and *Acanthoscelides obtectus* in different stored grains by generating and studying heat maps.

2.2 Non-imaging

Electronic Grain Probe Insect Counter (EGPIC)

It is an automated passive grain probe which provides real-time infestation monitoring and works like a Remote monitoring system for stored grain. It detects insect movement/activity within grain bulk. It has a probe, system circuitry, data logger and a user interface. The circuitry system detects even a slight declination of light intensity upon contact with an insect, converting it into a data (Epsky and Shuman, 2001) ^[22]. Wang *et al.*, (2025) studied electronic probe trap for detection of *Cryptolestes pusillus*. They also compared this with manual sampling and observed that electronic probe detected the pest better than manual sampling, at all the densities and moisture content.

3. Acoustic Based

Acoustic Detection

Acoustic detection is a non-destructive method which works on monitoring the sound made due to movement and feeding of insects to estimate the type and density of insects within a stored grain mass. Although, the efficacy of the equipment depends on type and frequency range of sensors used, size and type of insect and the distance between the insect and sensor (Mankin *et al.*, 2011) ^[36]. This method was used for detection of *S. oryzae* incidence, where the infestation was detected at a low level of 1.9 adults/kg (Mankin *et al.*, 2020) ^[37]. Balingbing *et al.* (2025) ^[8] detected *Rhyzopertha dominica*, *Sitophilus oryzae* and *Tribolium castaneum* using an acoustic device. Inclusion of various other techniques like machine learning and artificial neural networks (ANN) can improve the results giving high accuracy (Keerthana *et al.*, 2025) ^[28].

4. Conductance Based

Electrically Conductive Roller Mill

This technique works on the principle of electrical conductance and compression force to detect infestations in stored food products. Conductance of kernels is detected due to crushing of kernels between the rolls of the mill. The existence of adult insects within the kernel leads to an increase in the kernel moisture content, facilitating the differentiation between healthy and infested kernels. Brabec *et al.*, (2017) concluded this method to be suitable for quick detection of matured stages of larvae and pupae when 91% of medium larve and 81% of pupae of maize weevil were detected using this approach. Brabec *et al.*, (2023) used conductance mill to detect *Rhyzopertha dominica* at two different mill speeds. But before the experiment they used X-ray detection to detect the infested grains. These infested grains were checked at two different moisture content of

12% and 13.5%. They observed that as the moisture content increased the number of pests detected also increased.

Innovative Approaches for Pest Management

Detection alone does not solve the issue. After successful detection, appropriate management is also required. For that along with the conventional methods like use of gunny bags, using neem leaves and use of fumigants, various innovative methods are being used.

Modern Storage Structures

Using bins and gunny bags for storing grains has been practiced for a very long time. But this does not protect the produce efficiently from infestation. With advancement in human knowledge and research people started using different materials for building storage structures. Nowadays this has also been combined with controlled aeration and gas alteration inside these structures for further additional benefits. Hermetic storage and low-pressure structures are widely used in recent times (Gouthami *et al.*, 2024) ^[24]. Commercially available hermetic storage structures like silos, metal drums, hermetic cocoons and bags and polymer bags (Baributsa and Concepcion, 2020) ^[10] cause insect mortality due to asphyxiation by creating low O₂ / high CO₂ environment. Low pressure storage structures such as vacuum grain storage chambers, low-pressure fumigation chambers and industrial vacuum storage systems are the common low-pressure storage available (Guru *et al.*, 2022) ^[25] retard the insect growth and survival through rapid oxygen removal by artificial application of vacuum. Akshaya V.T. (2025) ^[3] evaluated different packaging bags to check population growth of cigarette beetle and weight loss in coriander seeds. Polythene bags were found to be most effective by reducing the weight loss to 12.44% as compared to the weight loss of 25.49% when gunny bags were used.

Physical Methods

a. Cold Plasma

It is an advanced non-thermal physical pest control technology consisting of an ionized gas containing reactive oxygen species (ROS), reactive nitrogen species (RNS), electrons and free radicals (Laroussi and Leipold 2004; Misra *et al.*, 2011) ^[35, 39]. These highly reactive components attack insects by damaging insect cuticle, cell membranes, proteins, respiratory tissues, DNA. Ziuzina *et al.*, 2021^[58] studied the effect of the atmospheric cold plasma exposure on the viability of *Tribolium castaneum* at different life stages. They observed the data at two time periods, i.e.; immediately after the treatment and 24hr after the treatment. In both the treatments the mortality was observed for all the life stages. This means that the cold plasma can be effective even after the treatment is stopped.

b. Ozone

Ozone has always been known to be used for various processes like water purification and sanitization of food (White *et al.*, 2010) ^[55]. In the same way it can be effectively used for eradication of pests from stored grains. It works as an excellent fumigant because of the ability to penetrate the grains and breakdown into O₂ without leaving any residues (Pimentel *et al.*, 2009) ^[45]. It has been proven to kill wide range of insects; both internal as well as external feeders (Constantine *et al.*, 2020) ^[20] like *T. castaneum*, *R. dominica*, and *O. surinamensis* (Sousa *et al.*, 2008) ^[49].

Amoah and Mahroof (2018) evaluated the effect of ozone on *Lasioderma serricorne* adults.

c. Irradiation

Irradiations like gamma-rays, x-rays and electric beams have been used for grain disinfection (Hallman, 2013) ^[26]. These radiations lead to DNA damage followed by sterilization, mortality, mutations and abnormalities in insects (Guru *et al.*, 2022) ^[25]. Despite being highly effective it is still not permitted to be used in every crop everywhere around the world because of being hazardous to human health. When *C. chinensis* adults were subjected to gamma radiation at doses of 0, 200, 300, 400, 500, and 600 Gy. Chilawal *et al.* (2019) ^[19] observed a decrease in female fecundity, hatchability, and adult fertility following the 300 Gy exposure. (Upadhyay and Mathur, 2022) ^[53] studied the effect of infrared irradiation on *Rhyzopertha dominica* for different irradiation time and distance. It was observed that the highest mortality was recorded as the distance and time increased.

Mechanical Methods

Semiochemicals

Semiochemicals are chemical signals produced by one insect/organism, which evokes behavioural or physiological responses in the receiving insect/organism. These are organic chemicals belonging to different chemical groups like alcohols, alkanes, sulphur-containing compounds, proteins *etc.* (Sharma *et al.*, 2019). These are used for various purposes like monitoring insect population, mass trapping, mating disruption and attracticide (Kline, 2007) ^[33]. Successful pheromonal studies under laboratory conditions were done in stored grain moths and stored grain beetles (Abd El-Ghany, 2019) ^[1]. Cao *et al.* (2024) investigated the behavioral responses of *Rhyzopertha dominica* adults and larvae to odour of different stored products in six-arm olfactometer bioassay. They observed that both the highest number of larva and adults were attracted towards wheat, concluding that the volatiles present in wheat can be used to develop lures or traps to manage *Rhyzopertha dominica*. Hasan *et al.*, (2023) evaluated the use of Exosex SP Tab auto-confusion plug impregnated with ZETA sex pheromone to manage Indian meal moth at seed warehouse and pet food store. They hung the confusion plug at a distance of 2-2.5 m above the ground so that the insects would easily come in its contact. They detected the mean number of *Plodia interpunctella* adults per pheromone trap at different trial sites treated and Mean number of *Plodia interpunctella* adults captured per pheromone trap one and two weeks before and after the dispenser deployment. In both the cases they observed that the number of moths captured per trap reduced after the deployment. These results indicate that the SP tab was successful.

Biological Agents

Using biological agents for managing the stored grain pests have been in practice since a long time. Commercially available entomopathogenic fungi are *Beauveria bassiana*, *Metarhizium anisopliae* and bacterium; *Bacillus thuringiensis* (Bt), which have been tested primarily against stored grain pests especially beetles (Batta, 2016) ^[11]. Protozoans like *Nosema whitei* (Milner, 1973) ^[38] and *Nosema plodiae* (Kellen and Lindegren, 1974) ^[32] have been reported long back to infest flour beetles and phycitine

moths respectively. Two important genera, *Steinernema* and *Heterorhabditis* proved effective against field crop pests and were also studied and found effective against stored-grain insects (Rumbos and Athanassiou, 2017) ^[47].

Phytocompounds

Since ancient times stored products have been protected against the attack of pests by using plant derivatives. The active compounds present in these plant materials act in several ways, including repellents, antifeedants, toxicants, and growth regulators (Guru *et al.*, 2022) ^[25].

a. Botanical Extracts

These are derived from various plant parts such as leaves, seeds, fruits and roots, botanical extracts contain bioactive compounds with insecticidal, fungicidal or herbicidal properties. Examples include neem oil, pyrethrum extract, and rotenone. Chauhan (2021) ^[17] studied the effectiveness of botanical powders against *Sitophilus oryzae* based on population growth during wheat storage. Different botanical powders *viz.*, Custard apple leaf powder, tulsi leaf powder etc. were evaluated at 2% concentration and it was observed that custard apple seed powder was the most effective and had the least number of adults emerged out even after 6 months.

b. Essential Oils

Essential oils or plant oils are extracted from aromatic plants through steam distillation or cold pressing. These contain volatile compounds that repel or kill pests. Essential oils like peppermint, eucalyptus and thyme are known for their insecticidal and repellent effects. Mode of action of plant oils involved mainly neurotoxicity, such as enzyme (Acetylcholine esterase) inhibition and neuromodulation (Guru *et al.*, 2022) ^[25].

Chauhan (2021) ^[17] also studied the effectiveness of plant oils as grain protectant based on periodical adult mortality of *Sitophilus oryzae* during wheat storage. It was observed that of all the different plant oils, castor oil at 0.5% resulted in highest mortality.

Insecticides

Although fumigants and synthetic insecticides are still widely used against stored grain insects, concerns over their environmental and health impacts have increased the need for safer and more selective modern pest control techniques (Athanassiou and Arthur, 2018) ^[6].

a. Insect Growth Regulators (IGR)

IGRs cause abnormal morphogenesis in insects by affecting embryonic and post-embryonic development as well as other biological processes like reproduction and behaviour. They are classified as molting hormone mimics, chitin synthesis inhibitors and ecdysteroid agonists (Mondal and Parween, 2000) ^[40]. Some commercially available IGRs are Methoprene, Chlorfluazuron, and Hexaflumuron *etc.*

b. Spinosad and Spinetoram

Spinosad (a mixture of spinosyns A and D) and spinetoram (mixture of spinosyns J and L) are produced as natural metabolites during aerial fermentation of *Saccharopolyspora spinosa*, a soil bacterium. The adult mortality of *S. oryzae* is reported to be 63.0% after 21 days in treatment with spinosad alone at 0.5 mg/kg (Gad *et al.*, 2022) ^[23].

Nanotechnology

Nanotechnology is increasingly being explored in both basic and applied sciences, including for the protection of stored

grains. Nanoparticles can be synthesized using various metals oxides such as zinc, silver, aluminium and others (Stadler *et al.*, 2018) ^[50]. Nanomaterials (NMs) and Nanoformulations (NFs) have shown unique properties such as enhanced barrier effects, controlled release and structural stability, which are critical in mitigating insect-pest infestations. El Saadony *et al.*, (2020) studied the insecticidal effect of ecofriendly synthesized copper nanoparticles against *Tribolium castaneum*. They compared the ecofriendly CuNPs with chemically synthesised CuNPs and found out that the Bio CuNPs resulted in maximum 100% mortality at concentration of 300µg/mL whereas the Ch CuNPs were not effective. Annon & Jafar (2020) ^[5] at evaluated the effect of pure and bio-synthesized silver nanoparticles, silica nanoparticles and *Nerium oleander* leaves extract on adult emergence of *Tribolium castaneum* and *Callosobruchus maculatus*. They observed that silica nanoparticles gave the best result by reducing the number of adults emerged out as the concentration increased. Adhikari (2023) ^[2] studied the effectiveness of non-edible oils and its nano-emulsions against *R. dominica* based on population growth. He tested 4 different oils and their nano-emulsions and noticed that the least number of adults emerged even after 180 days was found in neem oil nano-emulsions at 6% concentration.

Biotechnology

Molecular interventions involve gene-level pest control using RNA interference (RNAi) and CRISPR technologies. RNAi silences specific genes using dsRNA, while CRISPR-Cas enables targeted gene editing (Stathas *et al.*, 2023) ^[51]. These approaches show potential in pests like *Tribolium castaneum*, which can be attributed to easy multiplication in laboratory conditions and strong RNAi response at all developmental stages. Ning *et al.*, (2024) evaluated the expression patterns of antimicrobial peptides (AMPs) and phenotype of *Tribolium castaneum* after successful RNAi of *Tcctl13*. They observed that the larva in which the *Tcctl13* was knocked down showed increased mortality and also the expression patterns of antimicrobial proteins were down regulated. The treated larvae were not able to survive till the pupa stage. These results indicated that RNAi was effective in managing the insect.

Conclusion

Stored grain pests are a serious threat in global food security. Protection of stored products using modern detection techniques including sensor-based, imaging, acoustic and spectroscopic methods enables rapid and early identification of infestations, even at low levels, allowing timely intervention. Alongside this, management strategies that combine improved storage systems like hermetic storage, ozone treatment, microbial pesticides for biological control, insect growth regulators in chemical treatment, nanotechnological tools and molecular approaches like RNAi and CRISPR-Cas are being incorporated to ensure effective pest management. These approaches are being adopted in stored grain pest management across the entire post-harvest chain to minimize losses and maintain grain quality.

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