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Beyond fumigation: Unconventional technologies for sustainable seed and grain storage

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Introduction

Insect pests cause significant post-harvest loss of 5-10 percent seeds and grains in developed countries in comparison to 20-50 percent in developing countries (Mesterházy *et al*., 2020). Traditionally, storage insect pests are controlled using chemical pesticides especially the fumigants such as phosphine (PH3) and methyl bromide (CH3Br). Environmental risk posed by methyl bromide led to its restricted use only in quarantine. Overdependence on phosphine fumigation has led to resistance development in several storage insect pests (Deeksha *et al*., 2024). Moreover, human and environmental health hazards due to phosphine fumigation is also concerning. Phosphine is still one of the major causes of pesticide poisoning recorded in India (Kumar *et al*., 2025). Research across the world has been focusing to find a sustainable alternative to phosphine fumigation. Safe and green fumigants such as the ozone, ethyl formate and propylene oxide have been demonstrated for their potential to alternate phosphine in storage insect pest control (Maille *et al*., 2023). Biofumigants, plant product with fumigant action such as the essential oils from clove, garlic, mint have been explored for their usage in storage pest control. However, large scale replacement of phosphine has not been witnessed yet. In the search for chemical-free, safe and sustainable solutions for the pest management in storage environment, several novel technologies have developed around the world. Some of these technologies are commercialised and some are still in laboratory condition awaiting upscaling and field validation. The future of storage pest management may involve the physical forces existing in the universe such as heat, gases, electromagnetic energy, plasma, ultrasound, robotics, light, cold, vacuum and even magnetic fields. Stored product insects are biological organisms, but they live in a physical environment. Altering the temperature, oxygen, atmospheric composition, moisture, electromagnetic environment can drastically affect the survival of insects. Some of the technologies such as the cold storage, hermetic storage is commercially being used in seed and grain storage sector across the world. Moirangthem and Baik (2021) highlighted several non-chemical approaches including modified atmosphere, irradiation, and dielectric heating. Some of the potential unconventional storage technologies have been discussed in this article briefly.

Unconventional technologies for pest-free storage

1. Hermetic storage

Hermetic storage is one of the most simple and practical technology. It relies on airtight environment. In the absence of air exchange, respiration by commodities, insects and microorganisms gradually changes the internal atmosphere, reducing oxygen and increasing carbon dioxide. Hermetic storage does not require any sophisticated machinery or electricity of chemicals. Hermetic storage systems and bags are already available commercially. Damage to bags, poor sealing or repeated opening can allow atmospheric oxygen to enter and reduce effectiveness. A reliable sealing and monitoring system is essential for the success of the technology.

2. Modified atmosphere storage (MAS)

Instead of relying on respiration and other natural process for reducing oxygen as in hermetic storage, the atmosphere can be deliberately modified by reducing oxygen or increasing carbon dioxide or nitrogen. At low oxygen conditions, insects experience hypoxia. Increased carbon dioxide leads to hypercapnic stress. Research continues to investigate low-oxygen and nitrogen-based storage environments. Major challenge remains with maintaining the desired atmospheric conditions throughout the storage period.

3. Thermal treatment

Exposing insects to considerably high (or adequate temperature) temperature for sufficiently long duration leads to the death of insects. Thermal treatment can affect all the life stages, although their thermal tolerance varies. Challenge with the thermal systems is that, the high temperature that kills insects may eventually affect the seed viability as well. Success of thermal treatment remains with the identification of breakeven point, the minimum effective thermal dose at which the pests are killed and seed quality is maintained.

4. Cold storage

Cold temperature can suppress storage insects by reducing metabolism, feeding, development and reproduction. Sufficiently low temperature causes mortality in insects. An additional advantage is that cold temperature increases the longevity of many orthodox seeds. However, cost remains a major criterion. Refrigeration requires high capital investment and continuous energy input. Hence, cold storage is more suitable for high value seeds. Cold storage systems are highly commercialised in high value seed industries.

5. Radio-frequency (RF) heating

Radio-frequency (10 kHz and 100 GHz) heating works on the principle of dielectric heating. Wherein, materials of different moisture and composition heats at different frequencies. Research has demonstrated pilot-scale RF heating against *Tribolium castaneum*. Non-uniform temperature distribution remains a major challenge of this system. RF systems can also be expensive more suitable for specialised treatment facilities and pilot-scale systems.

6. Microwave and infrared

Microwave also generates heating through dielectric interactions within the material. Infrared transfers radiant energy to the exposed surfaces. Both electromagnetic waves can create rapid heating and rapid killing of insects. Microwave can produce hotspots as the moisture distribution affects energy absorption. Infrared waves have limited penetration making it suitable for shallow layers rather than deeply stacked seed bags. These technologies are viable for treatment during seed processing or handling than for treating the grain stacks in warehouse.

7. Cold plasma

An electrical discharge generates plasma containing reactive oxygen and nitrogen species. These reactive species can damage biological membranes, proteins and other cellular structures. Since the treatment is non-thermal, cold plasma is particularly suitable for those commodities that cannot tolerate high temperature. Thomas *et al*. (2026) studied the techno-economic parameters of atmospheric cold plasma as an alternative to conventional aluminium phosphide based grain storage practices. The economic viability depends strongly on the scale and stage of the grain-processing chain, with greater economic attractiveness for mills than for some drying and storage operations.

8. Robotics

Robots integrated with camera and artificial intelligence could identify the insect hotspots, classify the infestation and treat the affected location locally. Robotics provides precision detection and treatment options. Since many storage insects are hidden, the detection of internal grain infestation remains a challenge. With the advent of AI driven technologies, robotics may form a future platform for decision making and intervention (Zarboubi *et al*., 2024).

9. Laser and light

Optical systems that attract, detects the insect pests and direct a high energy laser beam to cause lethal damage has been developed in recent years (Adler *et al*., 2026). The attraction and detection is precise, chemical free and highly automated. Challenge remains with the internal feeding immature stages. The optical system can identify and direct a high energy laser beam towards a flying insects, but the hidden immature stages are left out. However, the laser and light system can be very useful for early detection and warehouse hygiene.

10. Acoustic and ultrasonic control

Insects respond to vibrations and acoustic signals. Sound-based methods have attracted attention for both detection and control. Recent research has investigated ultrasonic exposure against stored-product pests. A recent study by Awal *et al*. (2025) reported substantial repellency of rice weevil under specific near-far ultrasound treatments (33-48 kHz). A laboratory study investigated higher-frequency ultrasound (100 kHz) and reported considerable mortality under controlled conditions. Penetration of sound waves deep into the grain stacks remain a major challenge.

11. Magnetic field

Magnetic field is claimed to cause effects on cellular processes, oxidative balance and other physiological pathways (Hozayn *et al*., 2016) which will disrupt the insect life stages. However, evidence for reliable, practical control of stored-product insects is far less developed than other technologies.

Conclusion

The search for alternatives to the conventional fumigants does not rely on finding another insecticide. It is a search for a different way of thinking about the storage pests. The insect does not exist independently of its environment. Its survival depends on temperature, atmosphere, moisture and energy. By manipulating these physical conditions, it may be possible to suppress or eliminate pests while reducing dependence on conventional chemical treatments. Some of the technologies such as the hermetic storage, modified atmospheres, thermal treatment and cold storage already exist in practice. Other technologies such as RF heating, microwave treatment and cold plasma are moving towards large scale applications. Robotics, laser systems and acoustic technologies offer glimpses of a more automated future. The most promising pathway would be the integration of technologies rather than relying on a single method as a replacement.

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