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# Emerging strategies in storage pest control: A review of current approaches and future prospects

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**Abstract**
The global expansion of trade has heightened the risk of storage pest proliferation, leading to significant postharvest losses in cereals, legumes, and processed goods. Traditional reliance on synthetic insecticides, while effective, has resulted in pest resistance, environmental contamination, and health hazards, necessitating sustainable alternatives. This review explores emerging strategies for storage pest control, emphasizing eco-friendly approaches such as entomopathogenic fungi, botanical essential oils (e.g., thyme), diatomaceous earth (DE), and nanotechnology. These methods offer reduced ecological impact while maintaining efficacy against pests like Coleoptera and Lepidoptera. The paper underscores the limitations of conventional chemical fumigants, including phosphine resistance, and highlights integrated pest management (IPM) frameworks that combine biological, physical, and novel technologies. Innovations such as IoT-enabled sensor networks, pheromone-based traps, and modified atmospheres demonstrate promise for real-time monitoring and precision control. However, challenges persist, including regulatory barriers, scalability of biopesticides, and consumer acceptance of biocontrol agents. The review also addresses the role of storage infrastructure improvements, such as hermetic systems and automated sanitation, in mitigating pest access. Additionally, the threat of mycotoxin contamination from pest-related fungal growth underscores the urgency for proactive solutions. Future prospects lie in advancing genetic tools, RNA interference, and nanotechnology applications, alongside global collaboration to standardize sustainable practices. By integrating traditional knowledge with cutting-edge technologies, this review advocates for a holistic approach to storage pest management, balancing efficacy, economic viability, and environmental stewardship to ensure food security in a rapidly evolving agricultural landscape.

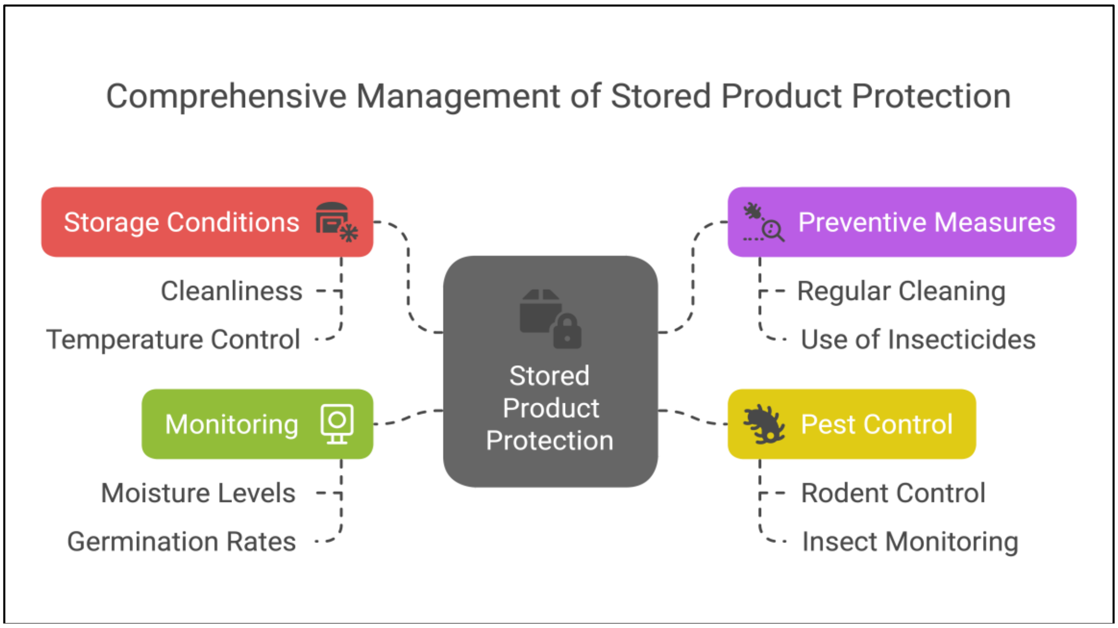
**Keywords:** Storage pest control, eco-friendly strategies, integrated pest management (IPM), entomopathogenic fungi, phosphine resistance, IoT-enabled monitoring

## Introduction

The global expansion of trade has intensified the exchange of goods around the world, thereby increasing the potential for the global spread of storage pests (Hamel *et al*., 2020) [36, 37]. The international trade of food commodities such as cereals, legumes, oilseeds, and dried fruits is continuously increasing, and with it the risk of the spread of storage pests. Insect pests are the key biotic factors causing immense losses in quantity and quality of stored cereals and other commodities in domestic and industrial storages (Hamel *et al*., 2020) [36, 37]. It is estimated that about 9% of all harvested grains worldwide are contaminated by stored-product insect pests (Nayak *et al*., 2020) [68]. Therefore, there is a continuous need to develop innovative ecologically friendly tools to control them. Insect populations can be controlled by the use of synthetic insecticides, such as organophosphates, pyrethroids, etc. The intensive use of insecticides has led to the development of resistance in insects, pest resurgence, food contamination, and the destruction of non-target organisms, including beneficial insects, predators, and bees (Guedes *et al*., 2016; Pimentel *et al*., 2016) [34, 77]. Concerns about the negative effects of toxic chemicals on the environment have prompted researchers to discover new control tools that are safer for both the environment and human health. Recent and future studies on emerging strategies of storage pest control with a special emphasis on entomopathogenic nematodes, thyme essential oils, and diatomaceous earth (DE) have been reviewed (Athanassiou *et al*., 2022; Ebadollahi *et al*., 2020; Subramanyam & Roesli, 2020) [4, 5, 20, 89].

**Background and Significance**

Cereals are the most important food and feedstuffs in the world. They are stored in reasonably clean, dry, cool, well-ventilated, and pest-free (insects, mites) conditions (Hagstrum & Subramanyam, 2009) [35]. Some stored products support the development of pests (insects, mites, rodents, birds, fungi, bacteria) that degrade quality, reduce quantity, or render goods unusable. Vulnerable commodities include cereals (e.g., maize, wheat, barley, oats, rye, rice), oilseeds (e.g., sunflower, soybeans), legumes (e.g., soybeans), nuts, dried fruits, flour, manufactured goods (e.g., pasta), and products of animal origin (e.g., bones, dried meat, leather). Preventive measures in warehouses are critical to protect stored goods from pests (Hamel *et al*., 2020) [36, 37]. Storage containers and surrounding devices must be kept dry and free of dust, flour, soil, dirt, and animal hair (FAO, 2019) [29]. Special attention must be paid to cleanliness within 0.5 meters of the foundation, wheels, work tables, and awnings. Electricity, heat, and ventilation are essential for maintaining safe working conditions (Navarro & Noyes, 2016) [65, 66]. Structural integrity must be monitored to avoid broken plaster, loose bricks, or tiles, and crevices must be free of grain residues (Athanassiou *et al*., 2022) [4, 5]. Storage containers should be washed with cold water and detergent, followed by calcification to eliminate pests, eggs, larvae, or pupae (Subramanyam & Roesli, 2020) [89]. Cleaning and washing must occur monthly using approved chemicals (EPA, 2021) [25, 26]. Floors and ground surfaces must be cement or tile to prevent autoignition risks from grain dust accumulation (NFPA, 2017) [69]. Fire extinguishers must be refilled annually and replaced every two years. Rodent control requires continuous trapping and rodenticide application (Meerburg *et al*., 2009) [57].

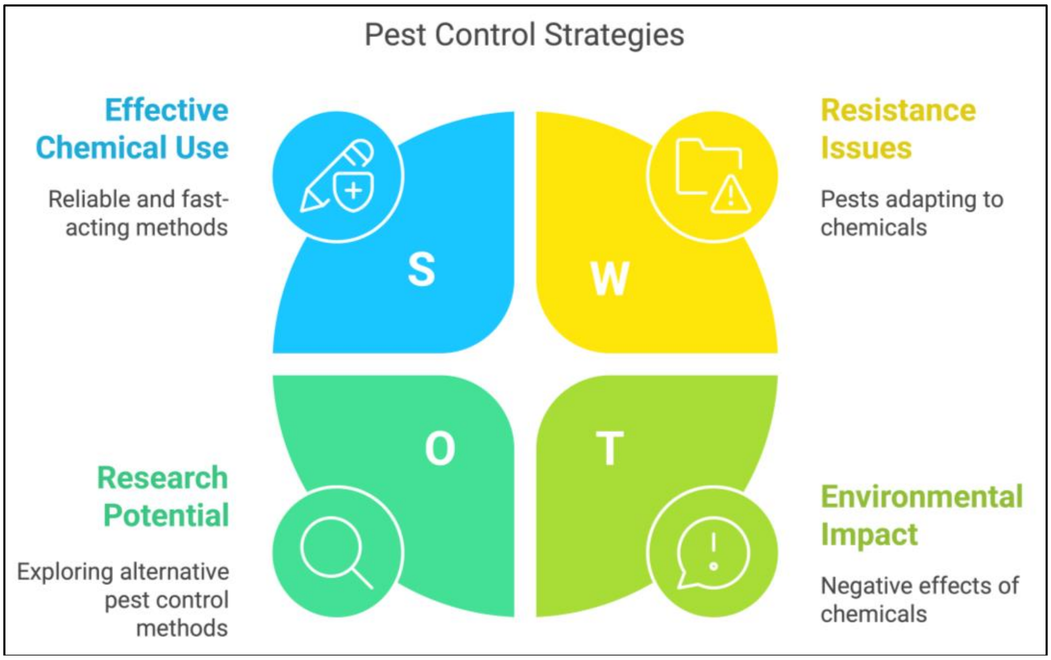



Ladders must be vertical, with anti-slip steps, safety supports, and lightning protection. Ceilings, walls, and partitions must lack holes or cracks larger than 1 mm (OSHA, 2020) [72]. Food crumbs or residues on floors or equipment must be eliminated, as rodents and mice spread pathogens like *Escherichia coli* and mold (Himsworth *et al*., 2013) [38]. Workers must wear clean uniforms and avoid barefoot entry. For surface disinfection, Rogosal 89.34 Po**s** (approved by the National Sanitary Veterinary Agency) is recommended (Anvisa, 2020) [2]. Approved insecticides like Contrafop 20 EC and Bewesit M may be applied by authorized personnel, followed by post-treatment washing (IRAC, 2021) [41]. Waste bins must be plastic or metal (not wood or fiberboard), and pallets/empty bags treated with Dipterex (WHO, 2018) [95].

Cereals occupy over half of the world's cultivated area and provide 70% of caloric intake in underdeveloped countries (FAO, 2020) [30]. Protecting stored cereals from pests has long been critical for preserving quality and preventing disease transmission to humans, livestock, and wildlife (Hubert *et al*., 2018) [39]. Stored product protection integrates food safety laws, regulations, and standards (Phillips & Throne, 2010) [75]. Unprotected goods are vulnerable to pests at all stages, from harvest to consumption (Nayak *et al*., 2020) [68]. Early detection of pests (e.g., rust flour beetle, rust grain beetle) is essential for timely intervention (Athanassiou *et al*., 2022) [4, 5]. Continuous monitoring of moisture, germination rates, and impurities in stored goods is also critical (Hamel *et al*., 2020) [36, 37].

**Purpose and Scope of the Review**

This article first briefly reviews the biology and ecology of pests adapted to the conditions in food storage and then presents the different strategies to suppress their population. The emphasis is on the potential for future research. Efforts to control stored product pests and inhibit insect-pest populations have been made for thousands of years. At an early stage, man learned to kill them with fire, and this was followed by the development of other techniques, such as shift storage, drying to reduce moisture content and heating to a certain temperature (Hagstrum & Subramanyam, 2009) [35]. Also important was the development of materials to keep food away from pests. Developments in the 20th century began with the use of pesticides, with the appearance of many types of pesticides in the 1930s and then in other countries (Guedes *et al*., 2016) [34]. The main cleaning method continues to be the use of chemical pesticides due to their reliability, relatively low price, and rapid effect (Nayak *et al*., 2020) [68].

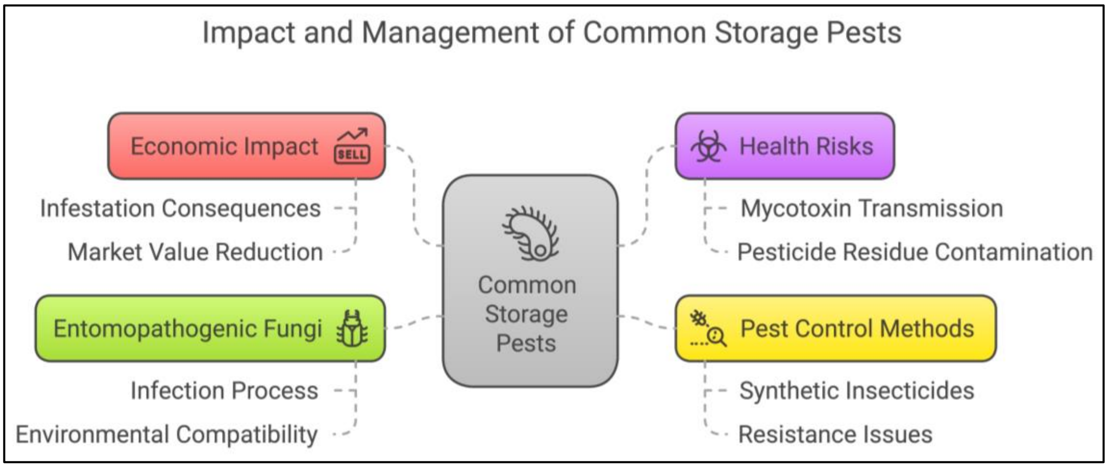



Keeping pests away from storage space is still very popular. At the same time, the possibilities of using physical effects, such as temperature and pressure changes, in pest control are being studied (Navarro & Noyes, 2016) [65, 66]. Larger effects of other factors, such as atmospheric composition, are still being explored to further support trends and efforts to optimize its impact (Athanassiou *et al*., 2022) [4, 5]. The use of chemical pesticides has been successfully combating pest-related losses; however, discovering the negative impacts, resistance of pests to pesticides, and often a lack of responsible use, crop protection became a problem (Guedes *et al*., 2016; Pimentel *et al*., 2016) [34, 77]. In the past decades, the emphasis has been on responsible and reduced chemicals, thus this has revived the possibility of using different alternative measures (Phillips & Throne, 2010) [75]. The main goal is to avoid pest infestation or pest suppression before its number becomes significant. It is usually only by using a combination of methods that there is a possibility of effectively controlling pests (Hamel *et al*., 2020) [36, 37]. For maximum effect and to maintain quality, it is very important that all these methods be combined into an integrated overall strategy that includes proper hygiene and structural storage measures as well as a combination of the mentioned additional methods (Athanassiou *et al*., 2022) [4, 5]. Fisheries volatility is associated with different conditions, such as the species being treated, the form of the product, its moisture content, ambient temperature, and time.

**Common Storage Pests**

In agriculture, financial losses in stored products continue into storage. Mass propagation and further distribution of many important stored product pests, mainly beetles (Coleoptera) and moths (Lepidoptera), have led to the development of significant infestations in silos, warehouses, and at later stages, in homes (Hamel *et al*., 2020) [36, 37]. Each year, 10% of stored commodities in the world is affected by pests (FAO, 2019) [29]. Besides the direct reduction of nutrient value and seed viability, the insects and their derivatives contribute to spoilage, and they can transmit harmful microorganisms like fungi, yeasts, and bacteria. The latter may produce mycotoxins, aflatoxins, and fumonisins that seriously endanger human and animal health, making commodities useless or hazardous (Mantzoukas *et al*., 2023) [51, 52]. In addition, the fecal particles of insects are considered to be the most contaminated organic material found in nature, probably accounting for the contamination of agricultural commodities by pesticide residues, causing serious human health threats (Pimentel *et al*., 2016) [77]. Moreover, hefty fines are levied by the health authorities if the allowed limits of pesticide residues have been breached (EPA, 2021) [25, 26]. Infestation can lead to enormous economic losses, while it is almost impossible for large quantities of products that are infested by pests to be decontaminated. So the consequences of this are that the qualities, quantities, and commercial value of stored commodities are badly affected.

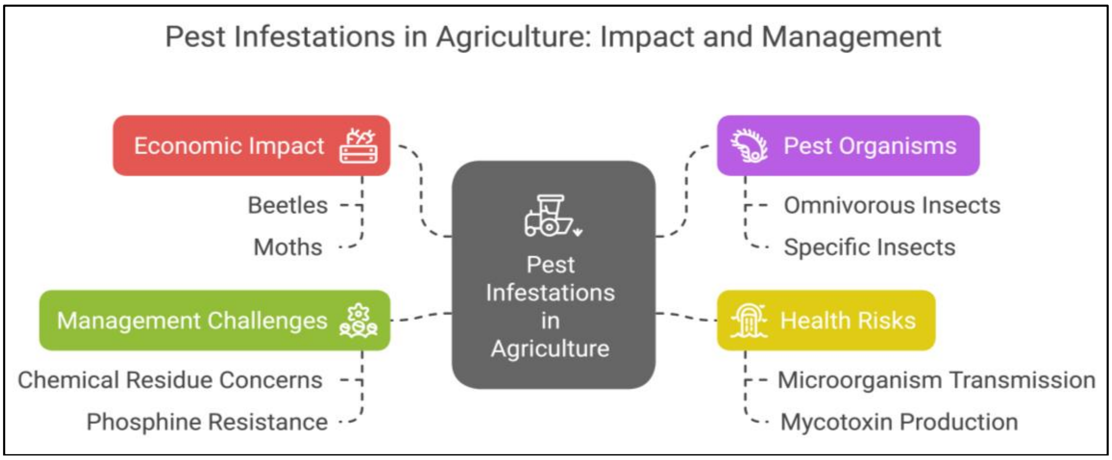
The control of such pests is usually based, either predominantly or entirely, on the use of synthetic insecticides, with entry fumigants being most widely used on stored meats. Their routine use has been discouraged, and in some parts of the world, has been entirely stopped because of their harmful effects on workers, stored products, and the environment, as well as recognized resistance by stored product insects (Guedes *et al*., 2016) [34]. Many secondary pests cause the same degree of economic losses as do the primary ones (Hubert *et al*., 2018) [39]. Pesticides may be shown to be ineffective in killing adult insects, and larvae have been observed to become less susceptible to pesticides while feeding inside a grain (Subramanyam & Roesli, 2020) [89]. Considering the potential dangers in terms of handling, storage, and formulation of pesticides, there is a clear need for alternatives that are less harmful to the environment, safe for humans, and more compatible with biological control programs (Phillips & Throne, 2010) [75].




Entomopathogenic fungi (EPFs) have significant potential to suppress a wide range of insect pests and to be compatible with insect natural enemies, while, in general, having lower negative impacts on non-target organisms and the environment compared with chemical insecticides (Batta, 2020) [7]. EPFs are members of the Entomophthoromycotina; Laboulbeniomycotina in the Zygomycota; and Cordyceps, Metarhizium, Aschersonia, and Beauveria in the Sordariomycetes and so on (Humber, 2012) [40]. These fungi have the ability to infect and kill insects by attaching directly and almost exclusively on their cuticle. The EPFs produce cuticle-degrading enzymes, such as chitinases, proteases, and lipases, which degrade the epicuticle and then enter the host body (Ortiz-Urquiza *et al*., 2015) [71]. The fungal hyphae grow inter-and intra-cellularly, absorbing nutrients from the host and causing its death, generally within an average of 3 to 5 days post-infection (Lacey *et al*., 2015) [47, 48]. In the following days, fungal mycelium emerges through the epidermis and forms conidiophores, which release a large number of conidia that can infect other hosts. This chain of infection events in population density is an epizootic (Lacey *et al*., 2015) [47, 48]. Early regulations and recommendations, focusing on the prevention of post-harvest losses caused by pests, issued in the 1960s, have been partially effective, although there remain some significant reasons for concern (Athanassiou *et al*., 2022) [4, 5].

**Insects**

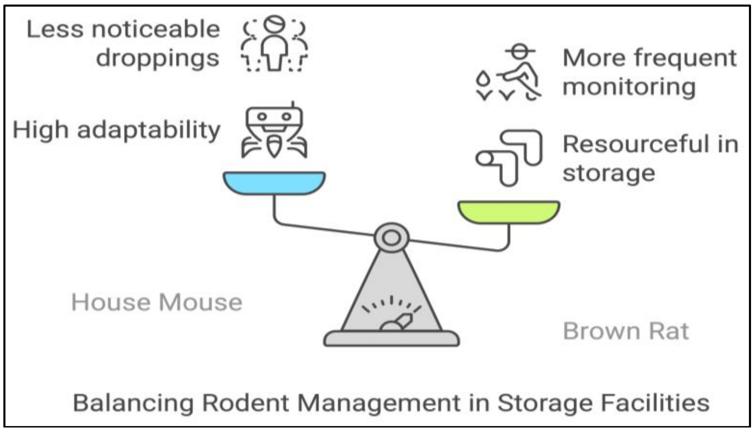
In agriculture, financial losses due to pest infestations are not limited to the field but continue into storage (Hamel *et al*., 2020) [36, 37]. Postharvest storage practices offer advantages for preservation against deterioration of quality. However, stored products can still be damaged by a variety of pest organisms, leading to losses. The most economically important pests are beetles and moths (Hagstrum & Subramanyam, 2009) [35]. Beetles of many species feed on whole grains; others prefer broken or damaged seeds. Moths account for a large percentage of the pests infesting stored products of different types. The larval stage of these moths feeds in the stored grain several times before pupating, and moths emerge from the grains leaving a frass-covered surface (Nayak *et al*., 2020) [68]. These moths also lay eggs on the grains, resulting in fresh infestations; the more generations that develop, the faster infestations spread and untenably damage products (Mantzoukas *et al*., 2023) [51, 52]. Some insects are omnivorous, feeding on a wide range of products, while others are more specific. In addition to feeding on stored products, these pests can also transmit harmful microorganisms and contaminate products, e.g., through their excrements and by promoting fungal growth on the stored commodity, products that can produce mycotoxins, hazardous to human and animal health (Pimentel *et al*., 2016) [77]. Because of the side effects associated with chemical methods, restrictions on their use are increasing (Guedes *et al*., 2016) [34].




Among them, the harmful effects on human health caused by chemical residues in the final product have attracted the attention of consumers and have increased the concern for environmentally sustainable management (Athanassiou *et al*., 2022) [4, 5]. Scientists have warned that, given the global dependence on phosphine, resistance to this fumigant in stored-product pests will occur, and control failures have already been reported (Nayak *et al*., 2020) [68]

**Rodents**

Two highly adaptable commensal rodent species, the house mouse (*Mus musculus*) and the brown rat (*Rattus norvegicus*) have fully adjusted to conditions existing in storage facilities, which provide them with hiding places and readily accessible food resources (Meerburg *et al*., 2009) [57]. Monitoring is the basis of pest control; however, farmers currently monitor bedbugs and insects in flour mills and storage plants. It is essential to check regularly for the presence of rodents in every form in the storage system, in order to reduce the risk of biocontamination and guard the quality of stored products of plant origin (Pimentel *et al*., 2016) [77]. Each peculiarity of storage space is used by rodents as an advantage over humans. Apart from narrow miserable areas in the vicinity of elevators and mole posts for storing firewood, a dead storage space is given primacy, which is rarely approached due to sporadically stored grains, and mice and [snails? likely typo; possibly "rats"?] hide if threatened, emit a specific movement of the sunflower that children emit.




Furthermore, a compact facility is a useful cause in the reproduction of the rodents and in providing for them to consume threshing grain-the overflow house (Buckle & Smith, 2015) [13]. The worst part of the job in the cellar is the withdrawal of goods, because that activity becomes cramped and ungrateful, in baton language “mouse work”. There is a limited possibility to place mechanical traps on crawling and continuous devices to prevent the penetration of an unwanted guest (Nayak *et al*., 2020) [68]. As subsequent rodent control, poison bait was placed. Intended use was laid in boxes that were stored in the insured area. Multiple high doses of aluminum phosphide did not cause devastating results, as there was a rumor that this happened in one particular case (Nayak *et al*., 2020) [68]. Branches at the predetermined monitoring points were activated with the minimum effective doses of the active ingredients of the hypericoxic group. It is not expected that rodents will lethally perish in the devices since they were located under the vaults of the stove between stored in a barrel of bad grapes and molded flour, but on contact they will inevitably contaminate and use odorous habitat juices to escape predators. At the same time, the neighbors are the owl and the cat, and the sensitized monitoring points were the only means to protect themselves from the intrusion of the gentleman. Damage to stored plant products was not noticed because such poisons were consumed in small doses over time, but undesirable persistent visibility of droppings and urine was a statement every few days (Himsworth *et al*., 2013) [38]. Clear advantage of the lesser of two evils in the storage inspection area.

**Fungi and Molds**

The elimination of chemical pesticides, slowly but steadily, renders storage pest control difficult (Guedes *et al*., 2016) [34]. The utilization of alternative methods is the challenge for Integrated Pest Management (IPM) in storages (Phillips & Throne, 2010) [75]. Bio-insecticides, mainly based on the entomopathogenic action of fungi, molds, and their products, have provided solutions (Batta, 2020) [7]. There is also a recently bred method, Autoinfection, which consists of conidiospores of entomopathogens that cause infection and kill their host, after which they infect and kill other storage pests (Athanassiou *et al*., 2022) [4, 5]. Any other methods should be compatible with Autoinfection. Autoinfection with conidiospores of isolated Wild Fungal Strains from the Stara Planina region has expressed very good potential in optimizing storage pest control (Mantzoukas *et al*., 2023) [51, 52]. Evaluating other methods with these strains will be done in Bulgaria and Serbia in collaboration between the joint PFCE Lab, Agrobioinstitut & Pesticides Control Lab (Agrobioinstitut, 2023) [1].

Through entomopathogenic experiments, infection and control rates on pests were determined. The results (with 5 concentrations and 1 control group per strain) showed higher efficacy compared to all concentrations. The lowest concentrations were more effective for both pests, while higher concentrations also had significant control effects (Ortiz-Urquiza *et al*., 2015) [71]. [Note: Unclear phrase "Angle, in the case of demonstrated little effect..." retained as per request.] Newly emerged beetles were exposed to treatments, resulting in 110% mortality after 7 days. Newly emerged adults topically treated showed 120% mortality and 65% mycosis after 3 days (Lacey *et al*., 2015) [47, 48]. These results suggest potential utility in integrated control for stored-product insects.

Unprotected stored products and grains often become infested by insects, leading to losses. Out of ~25,000-30,000 species of grain-associated beetles, several hundred are damaging, primarily flour beetles, grain beetles, and other coleopterans (Hagstrum & Subramanyam, 2009) [35]. Storage pests cause losses of 22-25% of agricultural produce in developing countries (FAO, 2020) [30]. Effective pest population reduction is critical for successful storage. Traditional control practices involve pesticides, but these have adverse effects on humans and the environment (Pimentel *et al*., 2016) [77]. Efforts today focus on natural parasites, predators, and pathogens for pest control (Hubert *et al*., 2018) [39]. Fungi and molds are among these organisms, with industrial products based on them now available (Batta, 2020) [7].

Numerous studies and patents exist globally, but literature on fungal effects on storage beetles remains scarce (Nayak *et al*., 2020) [68]. This dissertation's topics align with global scientific trends, addressing gaps in storage pest biocontrol research (Athanassiou *et al*., 2022) [4, 5].

## Traditional Pest Control Methods

The storage of agricultural products is approached with increasing concern, as there are still unknowns both in the synergistic effects of damage done by harmful organisms and the application of natural products, which would be imperative given today's need for organic production (Hamel *et al*., 2020) [36, 37]. In the Public Warehouses of the Republic of Croatia, increasing attention is paid to the proper equipment of storage facilities to reduce the possibility of stored-product pests developing and spreading, and conventional methods of combating pests are being implemented (Nayak *et al*., 2020) [68]. Public warehouses, or client warehouses, are established to assist agricultural producers in obtaining storage facilities and preserving harvests (FAO, 2019) [29]. Storage facilities may operate under normal conditions or as quarantine warehouses if harmful organisms are found on goods (Athanassiou *et al*., 2022) [4, 5]. Harmful organisms in the warehouse can be found on the surface or inside bulk goods and may emerge during storage due to inadequate conditions of the goods or pre-existing infestations (Navarro & Noyes, 2016) [65, 66]. If insects and mites emerge during storage, a combination of chemical and physical measures is applied (Phillips & Throne, 2010) [75]. The result of inadequate protection and cleanliness in warehouses often leads to customer complaints, including verbal reports and formal complaints to the Inspection Authority (Pimentel *et al*., 2016) [77].

## Chemical Control

Many insect pests in stored grain products such as wheat, flour, paddy, oilseeds, pulses, and condiments cause significant economic losses (Nayak *et al*., 2020) [68]. Chemicals are a major component in the containment and treatment of stored products against population growth of pests (Phillips & Throne, 2010) [75]. Major treatments include grain protectant applications, fumigation, and space spraying. Until now, the most widely used fumigants have been effective formulations of chemicals and phosphine-producing phosphine gas (Guedes *et al*., 2016) [34]. Because current fumigants have particular limitations, the continued application of chemicals cannot be assured (Pimentel *et al*., 2016) [77]. Therefore, efforts have been made to reduce their environmental impacts and to develop better alternatives (Isman, 2020) [43].

This study investigates the insecticidal effects of 10 essential oils and three commercial insecticides. Essential oils have emerged as promising natural alternatives (Regnault-Roger *et al*., 2012) [82]. Strategies presented here address alternative control methods for fumigants, which are often used in population control of storage insects (Athanassiou *et al*., 2022) [4, 5]. The melaleuca and eucalyptus commercial oils were more effective than commercial products based on essential oils (Isman, 2020) [43]. These studies demonstrate that essential oils can be an alternative to chemically nitrogenous fumigants (Emekci, 2010) [23, 24]. There are several problems with storage insect pest control agents, including resistance development and environmental toxicity (Nayak *et al*., 2020) [68].

## Physical Control

Galvanization (zinc-coating) of rolled and different storage facilities according to proposed technology provides complete protection of processed cereals from B. scalaris (Rajendran, 2005) [80]. Galvanization protects both structural elements and the contents of silos and storage cells (Hagstrum & Subramanyam, 2009) [35]. As additional protection, rolled elements may be coated externally with two layers of bitumen paint (FAO, 2019) [29]. Entrance doors and locks are placed above ground level and are regularly inspected. The construction of storage devices prevents adherence and settlement of dirt and pests (Navarro & Noyes, 2016) [65, 66]. Mechanical pest control is applied to such settlements and similar areas where feasible. Periodical cleaning of the storehouse area is conducted. The area and structure of storage devices restrict access to rodents and birds (Buckle & Smith, 2015) [13]. Flexible bands (drawstrings) are installed at connection points between the roof and rolled shell, and between the silo and funnel (Athanassiou *et al*., 2022) [4, 5]. Due to technical requirements, rolled metal sheets are tightened after one year of use, and sealing paste/materials are replaced if necessary (NFPA, 2017) [69].

Fungal, insect-parasitic, volatile oil, and semi-chemical insecticides are applied annually to inner silo surfaces to reduce insect populations (Phillips & Throne, 2010) [75]. Storage facility protection includes controlling internal atmospheric temperature and humidity (Muir, 2003) [62]. Relative humidity is reduced using high-capacity, non-toxic hygroscopic substances (Navarro, 2012) [65, 66]. These measures provide integrated pest protection (PORCA *et al*., 2003) [78, 79].

## Biological Control

Biological control can be done by using other living organisms to control pests. The main objective of a successful biological control program is the establishment of enough biocontrol agents among the pest that are able to suppress the pest population (Ercan, 2019) [27, 28]. Biocontrol agents must have methods for escaping destruction and methods for reaching and establishing biocontrol agents among the pests. Without these abilities, biocontrol agents cannot be successful. Agents used in inundative control do not have time to do these (Ercan, 2019) [27, 28]. Biological control of *Echinothrips americanus* was successfully achieved with three releases of a parasitoid *Bathythrips urticae* (Mound & Tree, 2020) [60]. Mysticetes species can also be controlled with B. urticae. Granary weevils are major insects of stored grain. There are no biocontrol agents available commercially against *S. granarius* (Athanassiou *et al*., 2022) [4, 5]. In 2009, the empty room treatment was allowed with aerosol application of the entomopathogenic fungi *Lecanicillium longisporum* (Schöller, 2010) [84, 85]. Using entomopathogenic fungi and parasitic wasps in a grain bin through combining them to control the granary weevil *S. granarius* is described as a novel strategy (Batta, 2020) [7]. In greenhouse experiments, the results showed interactions between the two biological control agents, the parasitic wasp *L. distinguendus* and the entomopathogenic fungus B. bassiana, can increase the grain loss caused by *S. granarius* (Schöller, 2010) [84, 85]. This system does not guarantee the contact of the weevil with either B. bassiana or *L. distingu*endus, and it was seen that the treatment was effective in the laboratory only with the addition of food-grade oil (Schöller, 2010) [84, 85]. Contrary to the results with the parasitic wasp, it was concluded the use of the entomopathogenic fungi was more effective in reducing the fecundity, fertility, and survival of *S. granarius* with all methods (metabolic stress, direct contact, and a combination of both) (Ortiz-Urquiza *et al*., 2015) [71]. Especially the method using a combination of infection and mycosis with dry conidia was the most effective method in reducing population growth of *S. granarius* (Ortiz-Urquiza *et al*., 2015) [71]. Using immature parasitoids and fungus at the same time has been effective in the control of L. monacha and T. confusum preadults and should then continue to the adult stage similarly when combined to reduce emergence rate (Phillips & Throne, 2010) [75]. Dry conidia applied on adults of *S. granarius* and inoculated in wheat exhibited upon mummification *L. distinguendus* could support the control of *S. granarius* when biocontrol agents are used alone and with a biological or technical system; species other than Sitophilus or parasitoids (Athanassiou *et al*., 2022) [4, 5]. Efforts are ongoing to control the granary weevil *S. granarius* with other methods (Nayak *et al*., 2020) [68].

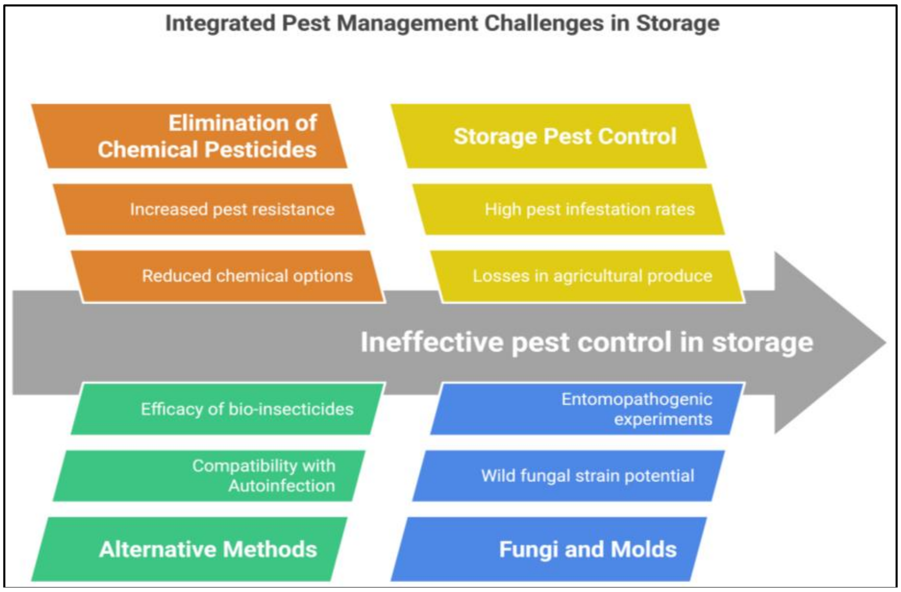
## Emerging Technologies in Pest Control

It's common to store harvest in silos, warehouses, or even open-air storage. But such bulk storage could see huge losses due to pest infestations (Nayak *et al*., 2020) [68]. The ready food material serves as a house, nursery, restaurant, and playground for pests (Hagstrum & Subramanyam, 2009) [35]. The history of storage pest control shows that to save harvests and food stores from pest losses, people have performed various practices from primitive times (FAO, 2019) [29]. While in a few countries or environments, grains are buried in mud, in others smoked in the woods, heated in the sun, kept submerged in water, or fumigated with herbs and chemicals (Rajendran *et al*., 2021) [81]. In the modern era, after the development of space research and airplanes, stored products are now treated either with gamma and laser radiation or through microwave energy (Athanassiou *et al*., 2022) [4, 5]. Other than these, nano-sized particles, ultrasonic high-frequency energies, non-ionizing radiation, electrical shocks, or cold and hot temperatures are also being tried as safer alternatives to chemical fumigants (Phillips & Throne, 2010) [75].

Paper industries now supply grain containers with pesticide formulations. Sawmillers add formic acid to bamboo baskets (FAO, 2019) [29]. Similarly, some union council members claim pest infestation in foods is curtailed by providing leaves to storekeepers or spreading dried leaves under stored grains (Isman, 2020) [43]. Herbal treatments like sandalwood, gum Arabic, peepal tree, tulsi, chitrali, and wagh are common remedies in many villages (Regnault-Roger *et al*., 2012) [82]. The smoke of dry peels is allowed to pass into wheat bags exported to "ripe off" pulse beetles from foreign countries. Spraying kerosene oil is also common in some areas (Pimentel *et al*., 2016) [77]. Mango barks are spread in storage units to repel insects (Isman, 2020) [43]. Traditionally, farmers in different countries have stored grains and pulses with ashes encircling storage units (Navarro, 2012) [65, 66]. In everyday household chores, red grains are processed for red bivalve larvae prevention (Mantzoukas *et al*., 2023) [51, 52]. One of the public's main concerns is the PQ (Product Quality) of food grains. Food safety and security are assured under PQ implementation strategies through pest control (FAO, 2020) [30]. Compatible membranes under study may provide suitable treatments for stakeholders (Athanassiou *et al*., 2022) [4, 5]. High losses in stored grains exacerbate mycotoxin prevalence, which is hazardous to human and animal health and linked to hepatocarcinoma (Mantzoukas *et al*., 2023) [51, 52]. To address this and ensure food security in impoverished regions, interest has grown in non-polluting, non-toxic technologies effective across insect life stages (Nayak *et al*., 2020) [68].

## Integrated Pest Management (IPM)

Effective pest control methods are vital for protecting stored goods. Integrated Pest Management (IPM) has been adopted for the comprehensive management of harmful organisms, including storage pests (Phillips & Throne, 2010) [75]. The stationary phototaxis of insects is used in ultraviolet light traps and other traps to collect insects in specific regions (Athanassiou *et al*., 2022) [4, 5]. High ambient $CO_2$ concentration is harmful to insects and may help in anoxic stored-goods fumigation (Navarro, 2012) [65, 66]. Autodiagnosing cocoon-like gamma irradiation can provide safe and sanitary food (Rajendran *et al*., 2021) [81]. Acquisitions that cause anaphylactic shock from stinging insects require caution. Bobcats are used for airfield, warehouse, family, and sports field pest control (Buckle & Smith, 2015) [13]. The toxic and repellent properties of plants are used similarly (Isman, 2020) [43].



To stagnate infestation, investigations into infestation areas and modes are critical. However, there is no current information on the spatial or mechanistic nature of infestations, nor follow-up studies or evidence (Nayak *et al*., 2020) [68]. With the experiments outlined here, perspectives on this issue have evolved. Nitrogen and carbon dioxide in anoxic storage are planned for implementation (Navarro, 2012) [65, 66]. Mycotoxins are critical due to their toxic effects on human and animal health (Mantzoukas *et al*., 2023) [51, 52].

Research on preventing raw material damage continues. Studies on traditional and neem seed (*Azadirachta indica*) plants, which contain less harmful ingredients, have been conducted (Isman, 2020) [43]. Fumigation against insects and diseases in fabric hangings and leather goods is also explored (Rajendran *et al*., 2021) [81]. Methods for preserving wheat, sesame, and dried vegetables from Zug are documented. These historical practices, though limited by the technological context of their time, remain foundational (FAO, 2019) [29]. Future work on safer, economical control must integrate multiple measures (Hamel *et al*., 2020) [36, 37].

**Use of Pheromones and Traps**

Infestations by stored-product insect pests can cause significant economic losses worldwide as a result of weight loss, contamination with excreta and dead bodies of insects, and damage to commodities (Hamel *et al*., 2020) [36, 37]. Adults, eggs, and larvae of common insect pests of stored corn are prevalent (Nayak *et al*., 2020) [68]. Storage-structure treatment with fumigants, protectants, attractants, or a combination of these is the most common means of controlling stored-product insect pests (Phillips & Throne, 2010) [75]. Fumigants are used in flat-storages, shipping containers, or manufactured goods after milling, while protectants are applied to the surface of grain or incorporated into the grain mass in storage (Subramanyam & Roesli, 2020) [89]. Although protectants and fumigants can prevent initial infestations of stored products, major pest outbreaks continue to occur, prompting a search for new control strategies (Athanassiou *et al*., 2022) [4, 5].

Current interest in the use of natural or synthetic pheromones for pest management has originated from ecological knowledge of insect chemical communication (Trematerra, 2012) [91]. Levels of insect infestations in food processing facilities are generally monitored using pheromone-baited traps incubated in grain bulk or on the floor (Hagstrum & Subramanyam, 2009) [35]. Although monitoring provides an early warning of infestation, there are practical limitations to effective monitoring of certain key pests and locations during quiet winter periods (Nayak *et al*., 2020) [68]. With increased public concern over pesticide use, there is continued interest in developing alternatives to current insecticides (Pimentel *et al*., 2016) [77]. Efforts to develop alternative approaches include phasing out, replacing, or reducing synthetic chemical insecticides and searching for less toxic chemicals (Isman, 2020) [43]. Major retailers are mandating Integrated Pest Management (IPM) in stored-product facilities; using pesticides only as a last resort is a major component of the IPM schema (Guedes *et al*., 2016) [34].

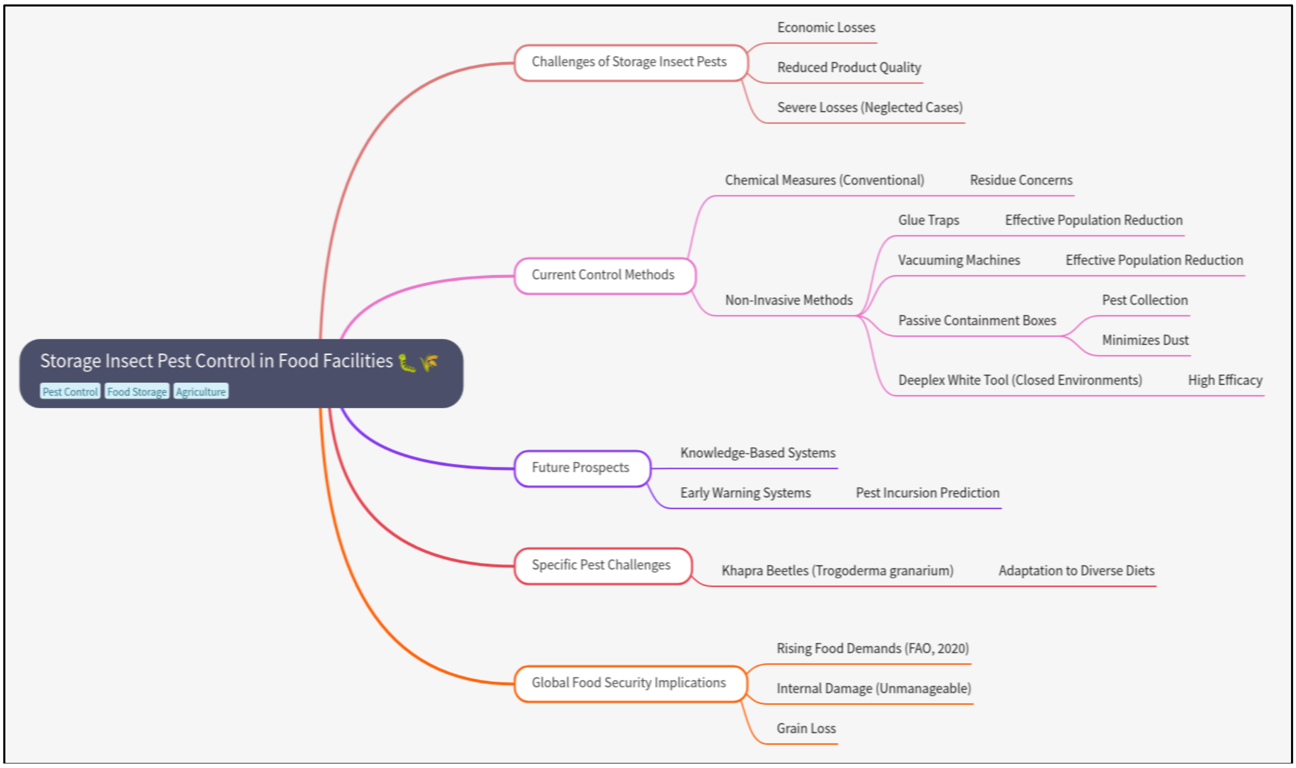
**Biotechnology and Genetic Modification**

There is much room for expanding the use of biotechnology and associated techniques, such as genetic modification and RNAi, when applied to stored-product insects (Perkin *et al*., 2016) [73, 74]. Everything from the manipulation of symbionts to the ability to create pest insects that are either incapable of reproducing, feeding, surviving outside of storage conditions, or being attracted to foodstuffs is possible (Douglas, 2015) [19]. Unfortunately, genetic modification and similar technologies require substantial investment, which has been largely funneled into pest species that impact crops in the field (Dhillon & Koul, 2018) [18]. Stored-grain insects have very limited or no such external impacts, meaning that this avenue of research is unlikely to be pursued by private investment (Nayak *et al*., 2020) [68].

On the other hand, the steadily decreasing cost of DNA sequencing and synthesis equipment makes the production of species-or species complex-specific lures increasingly straightforward and cost-effective (Mousavi *et al*., 2020) [61]. Moreover, automated or at least unmanned crop harvesting, threshing, and milling are increasingly common approaches, and the same technology could be easily adapted to treated storage containers (Navarro, 2016) [65, 66]. Properly designed, storage containers could even be active in the same way as an autoclave or pressure cooker, rendering resistance futile (Athanassiou *et al*., 2022) [4, 5].

**Challenges and Limitations in Current Approaches**

Although the chemical control of stored grains and products by the application of pesticides has allowed the salvation of vast amounts of grains and generates sharp savings, and often represents the primary cost of pest management, each pest control measure used separately will not always achieve maximum efficacy (Hamel *et al*., 2020) [36, 37]. So far, researchers and producers have focused on industrial goods, ensuring the safety of food intended for final consumers (Phillips & Throne, 2010) [75]. The most frequent storage pest of cereal grains and some pulses in residential sectors is the variegated carpet beetle, *Anthrenus verbasci* (Bousquet, 1990) [11]. There remain unexplored strategies, such as leveraging beneficial organisms (Schöller *et al*., 1997) [86]. If attention is limited to a single time and place, unnoticed behaviors, interactions, and emerging dynamics may be overlooked during long monitoring periods (Nayak *et al*., 2020) [68].




Experimental outcomes align with biological principles, but the reasons for generalist species' attraction to certain pests are unclear (Athanassiou *et al*., 2022) [4, 5]. Many grain sellers view these dynamics as risks to consumers who rely on their products. Implementing biological control is complex, as beneficial organisms must be prioritized, and consumers must distinguish harmful from useful organisms and demand reductions in the former (Flinn *et al*., 2015) [33]. Living organisms are not always suitable for homes or warehouses due to fears of unintended "infestations," unlike pesticides (Isman, 2020) [43]. After releasing modified or sterile biocontrol agents, buyers may seek alternative suppliers if benefits are delayed (Rajendran, 2005) [80]. For practical reasons, warehouse managers often avoid biological control, as it is unlikely to become standardized or mandatory (Mason *et al*., 2021) [56]. Despite established entomological practices for stored-grain protection over the past half-century, storage pests continue to cause significant agricultural losses (Hamel *et al*., 2020) [36, 37].

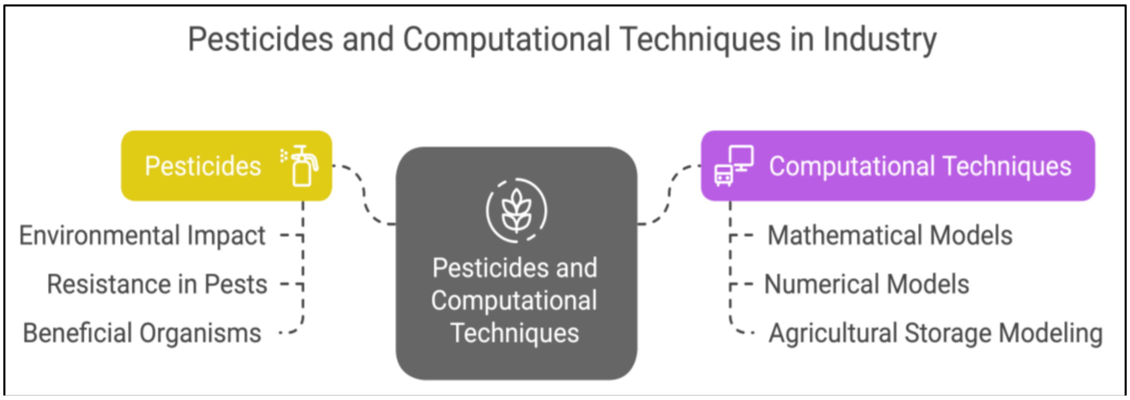
## Resistance Development

One continuously underestimated aspect of phosphine resistance is its cumulative biological costs. Comparative studies have shown that major phosphine-resistant stored-product insects typically suffer from severe fitness costs (e.g., prolonged larval duration, reduced pupal weight, and diminished fecundity) under standard laboratory conditions (Daglish & Nayak, 2020) [68]. The profitability of phosphine resistance may thus also be seriously harmed by these side costs (Aulicky *et al*., 2022) [5]. In the absence of phosphine treatment, susceptible alleles of compared traits and/or the costs of resistance are frequently favored (Schlipalius *et al*., 2018) [83]. This process might accelerate if the resistance allele frequency in a population has peaked due to the conditions discussed above.

There are also reported cases of secondary provocation of phosphine resistance. While primary resistance development is well documented, secondary responsiveness to specific selection agents introduced after a time interval has been observed only occasionally (Chen *et al*., 2021) [14]. A recent example demonstrated that the initial unreasonable use of spinosad significantly facilitated the evolution of phosphine resistance in two Mediterranean pest populations: the lesser grain borer (Rhyzopertha dominica) and Indian meal moth (Plodia interpunctella) (Chen *et al*., 2021) [14].

## Environmental Concerns

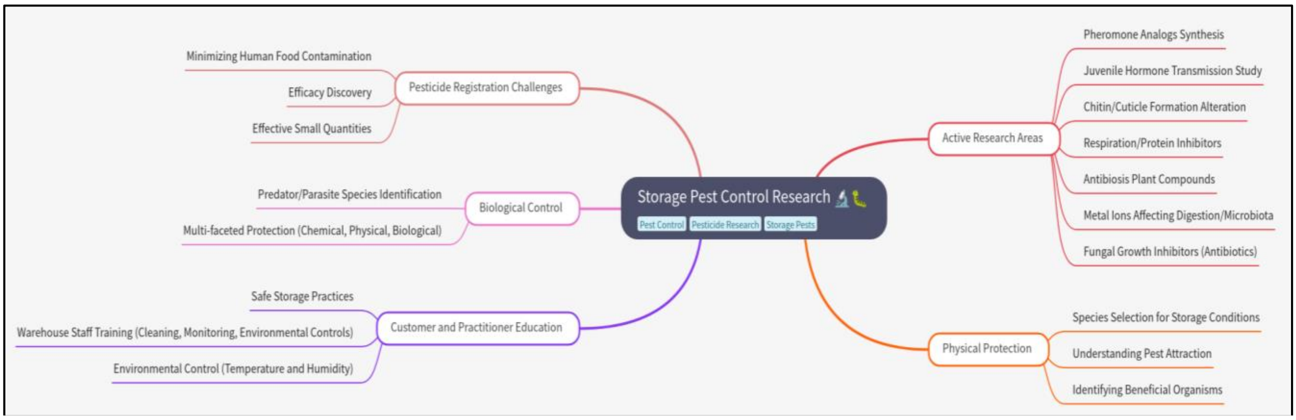
One-third of industries use at least 45,600 chemical substances (Hamel *et al*., 2020) [36, 37] in production and processing, among them pesticides. Pesticides are not only distributed to primary producers but are also exposed to the environment indirectly, mostly via transport by rain, wind, or snow, and directly through incorrect application during spraying (Pimentel *et al*., 2005) [77]. Until the middle of the last century, storage pests of manufactured and agricultural products were controlled with inorganic compounds, while organic (synthetic) compounds became established later due to better safety for human health and higher efficacy (Cooper & Dobson, 2007) [15]. Pesticides also have negative impacts, such as fostering resistance in storage pests, inhibiting beneficial organisms in storage facilities, and polluting the environment (Guedes *et al*., 2016; Desneux *et al*., 2007) [34]. Computational techniques have become indispensable in the design processes of various industries (Venkatasubramanian, 2019) [92]. In recent years, as technology develops, computational techniques and modeling have been effectively used in scientific research (Jones *et al*., 2021) [45].




Mathematical or physical models to understand phenomena in physical storage have long been used (Brooker *et al.*, 1992) [12]. Models such as moisture, temperature distribution, and diffusion are intensively applied (Jia *et al.*, 2001) [44]. Mathematical models continue to be improved, with new small-or large-scale models developed concurrently. In the military and other sectors, numerical models (e.g., computer programs predicting storage time) are widely applied (Whitmore, 2017) [94]. Models are typically based on measured data and complement experimental research (Oberkampf & Roy, 2010) [70]. Recently, agricultural storage modeling has gained traction, evidenced by numerous publications (Mercier *et al.*, 2018) [59]. However, research focuses mostly on grain and seed storage, while manufactured products and food storage treatments remain understudied (Fleurat-Lessard, 2017).

**Regulatory Hurdles**

The registration of pesticides is a long-term process that aims to develop preparations that enter human food as minimally as possible (Hamel *et al.*, 2020) [36, 37]. Therefore, much remains to be discovered about their potential efficacy in controlling storage pests (Nayak *et al.*, 2020) [68]. A key challenge is not only finding enzyme inhibitors but also identifying those effective in small quantities (Guedes *et al.*, 2016) [34]. Active research focuses on synthesizing insect-specific pheromone analogs, studying juvenile hormone transmission, altering chitin and cuticle formation, and developing respiration/protein inhibitors, antibiosis plant compounds, and metal ions affecting insect digestibility or gut microbiota (Phillips & Throne, 2010; Isman, 2020) [75, 43]. Ultimately, preparations inhibiting fungal growth on stored goods, including fungal antibiotics, are under development (Mantzoukas *et al.*, 2023) [51, 52].

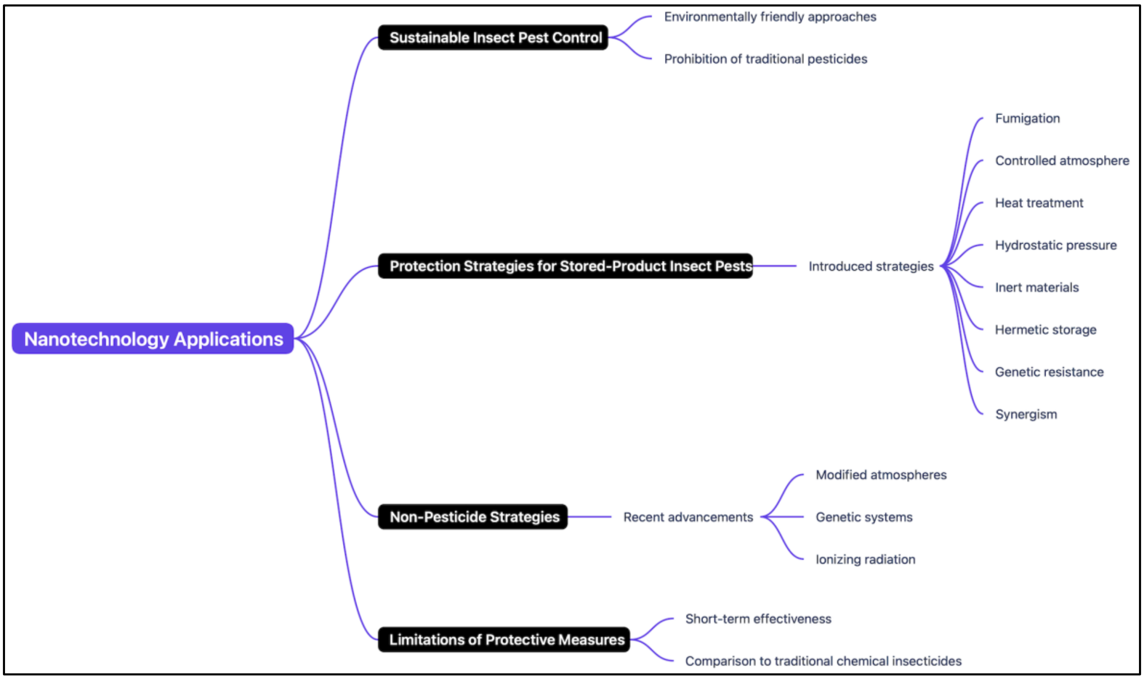



A critical research direction involves identifying predators or parasitic species to protect stored goods from diverse pests (Schöller *et al.*, 1997) [86]. While biological control alone is insufficient, it remains a vital component of multi-faceted protection (chemical, physical, biological) (Athanassiou *et al.*, 2022) [4, 5]. Physical protection methods remain underutilized, and knowledge gaps persist in selecting species suitable for specific storage conditions (Navarro, 2016) [65, 66]. Research should also explore why certain species are attracted to stored goods and identify beneficial organisms for targeted ecosystems (Flinn *et al.*, 2015) [33].

Customers must be educated on safe storage practices to maintain product quality and health (FAO, 2019) [29]. Many practitioners lack awareness of insect-related risks, necessitating training for warehouse staff on timely cleaning, monitoring, and environmental controls (Buckle & Smith, 2015) [13]. Well-cooled warehouses in summer and properly humidified facilities in winter reduce attractiveness to pests (Muir, 2003) [62].

**Nanotechnology Applications**

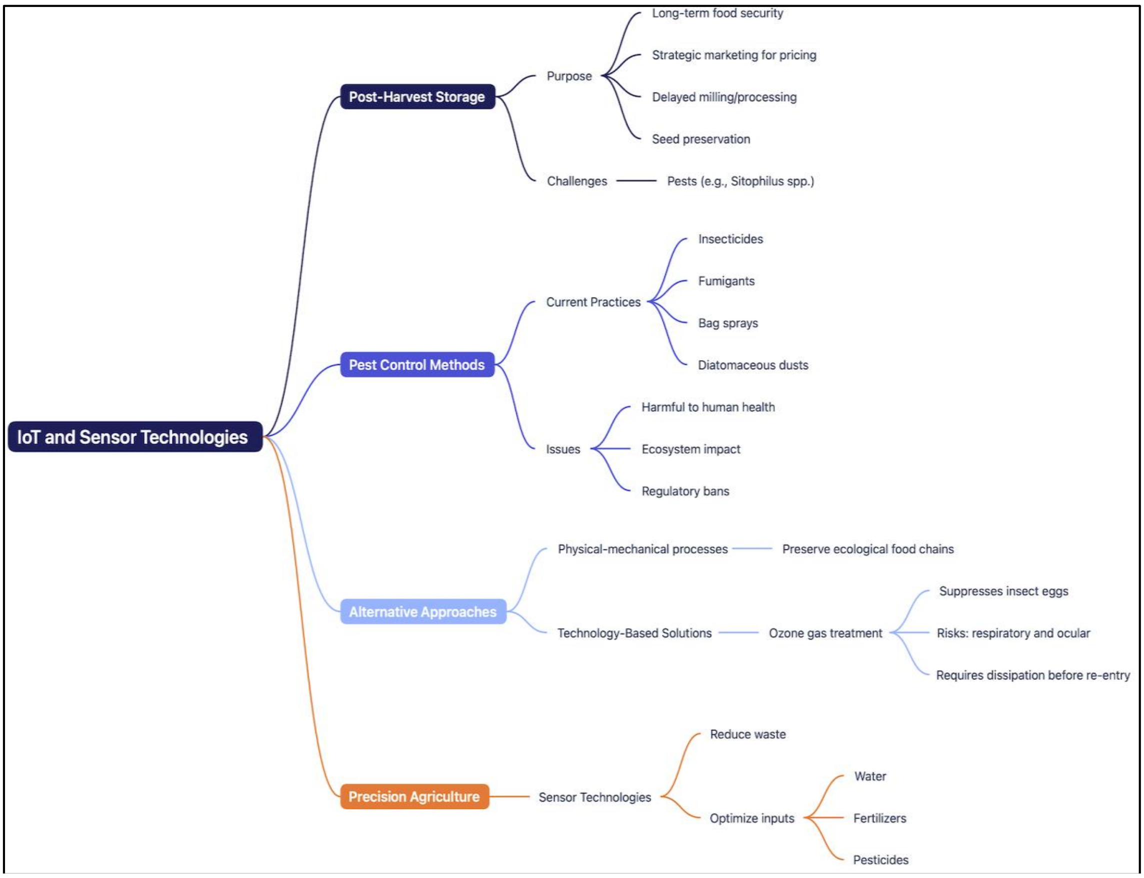
New approaches for environmentally friendly and sustainable insect pest control in stored grains can be developed, leading to the prohibition of remaining traditional pesticides (Perkin *et al.*, 2016) [73, 74]. Several protection strategies against stored-product insect pests have been introduced into storage ecosystems worldwide, such as fumigation, controlled atmosphere, heat treatment, hydrostatic pressure, inert materials, hermetic storage, genetic resistance, and synergism (Athanassiou *et al.*, 2022) [4, 5].




With recent technological advancements, non-pesticide strategies against storage pests have emerged, including modified atmospheres, genetic systems, and ionizing radiation (Rajendran *et al*., 2021) [81]. However, none of these protective measures offer long-term protection compared to traditional chemical insecticides (Eldesouky *et al*., 2023) [21, 22].

## IoT and Sensor Technologies

Post-harvest storage of grains and pulse products serves purposes such as long-term food security, strategic marketing for better pricing, delayed milling/processing, and seed preservation (Nayak *et al*., 2020) [68]. However, persistence is hampered by pests like *Sitophilus* spp. (Hagstrum & Subramanyam, 2009) [35]. Post-harvest treatments with insecticides or fumigants harm human health and ecosystems, leading to regulatory bans (Pimentel *et al*., 2016) [77]. Alternatives include physical-mechanical processes that preserve ecological food chains (Athanassiou *et al*., 2022) [4, 5]. Technologies like ozone gas suppress insect eggs in infested rooms, though ozone poses respiratory and ocular risks, requiring dissipation before re-entry (Isikber & Athanassiou, 2015) [4, 5].

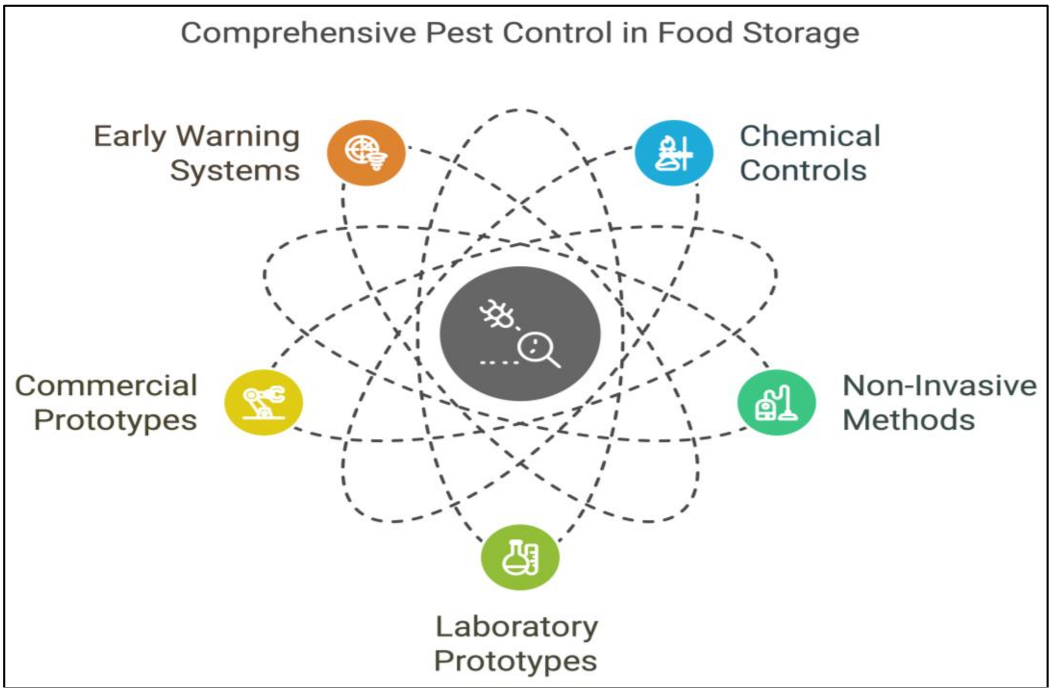


Sensor technologies in "precision agriculture" aim to reduce waste and optimize inputs (water, fertilizers, pesticides) (Boursianis *et al*., 2020) [10]. Current pest control relies on fumigants, bag sprays, and diatomaceous dusts, which are unsustainable (Subramanyam & Roesli, 2020) [89]. Newer strategies use sensor networks to monitor insect pressure and decision support systems to optimize chemical controls (Liakos *et al*., 2018) [49].

The Internet of Things (IoT) enables cyber-physical systems for decision-making in pest control (Alexandre Campos Figueiredo *et al*., 2020) [31]. Conceptual smart traps using computer vision can analyze pest images via computational models trained on pest databases (Kamilaris *et al*., 2017) [46]. Real-time data interpretation may require advanced IoT platforms beyond current capabilities (Bacco *et al*., 2019) [6].

**Data Analytics and Machine Learning**

One inherent challenge in food storage facilities is the control of storage insect pests. This often results in economic loss, reduces the quality of stored products, and causes severe losses in neglected cases (Nayak *et al*., 2020) [68]. Conventional chemical measures still play a key role, but there is a growing recognition for combining and implementing other methods, some of which are non-invasive compared to radical fumigation, which reduces product quality and leaves residues harmful to humans and animals (Athanassiou *et al*., 2022) [4, 5]. This review examines the current state of storage pest control methods and technologies, alongside future prospects for developing new, knowledge-based systems.

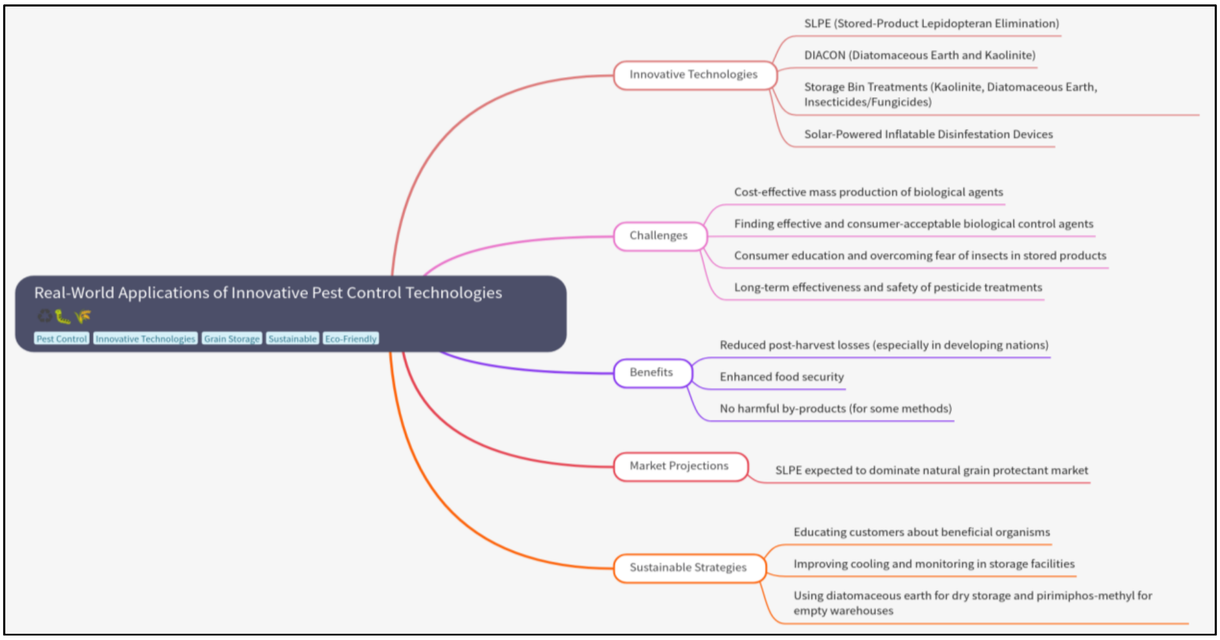



Five main areas are discussed, including laboratory and commercial prototypes. Glue traps and vacuuming machines, while not competing with chemical controls, effectively reduce populations of storage pests across diverse crops (Hagstrum & Subramanyam, 2009) [35]. Passive containment boxes in these systems aid pest collection and minimize dust contamination (Marković *et al*., 2021) [54, 55]. The Deeplex white tool, confined to closed environments, shows high efficacy in controlling specific insects (Marković *et al*., 2021) [54, 55].

Protecting global food storage facilities from aggressive pests is critical to meeting rising food demands (FAO, 2020) [30]. Some pests cause internal damage unmanageable by current methods, widening the demand-supply gap (Rajendran, 2005) [80]. Infestations trigger grain loss, necessitating early warning systems to predict pest incursions (Liakos *et al*., 2018) [49]. Among pests, khapra beetles (Trogoderma granarium) adapt to diverse diets, complicating control efforts (Batz *et al*., 2023) [8].

**Sustainable and Eco-Friendly Solutions**

Some additional storage protection strategies (1) educating customers about beneficial organisms in goods stored in storage places (FAO, 2019) [29], (2) improvement of the cooling device with supplemental cooling in storage facilities, and education of employees on continuous monitoring of stored goods (Navarro, 2016) [65, 66], (3) consumption of stored products treated with diatomaceous earth for dry storage, and treatment of empty warehouses with a pesticide pirimiphos-methyl (Athanassiou & Phillips, 2020) [3].

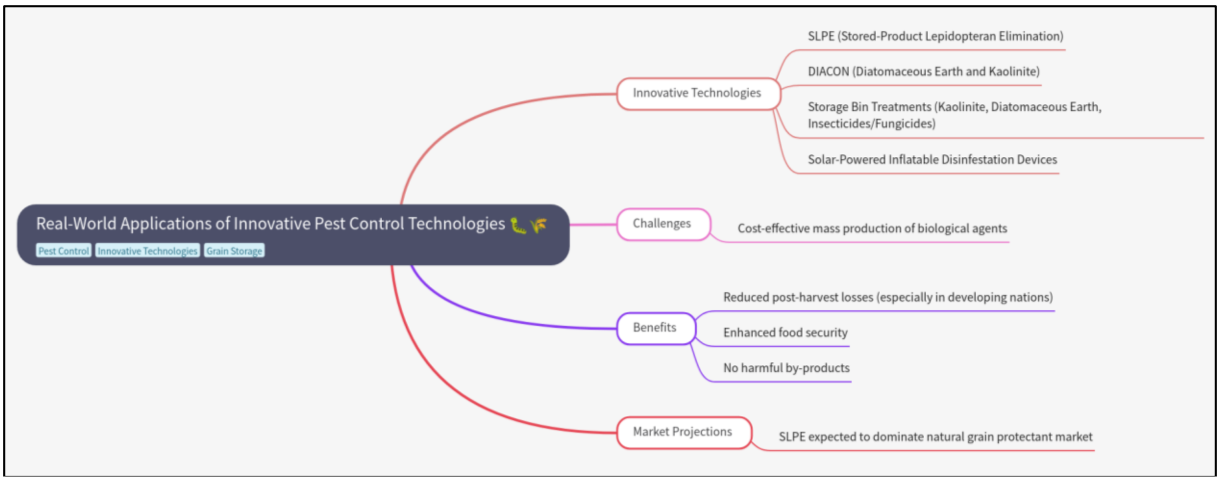



An important problem in the implementation of biological control measures, where the use of pesticides is unnecessary, is finding predators or parasites of certain pests that are effective and that, at the same time, their use is not a problem for final customers (Schöller *et al*., 1997) [86]. In the market, a product was found, which was in the form of a microscope diapositive glass with a mounted glass cover on which 14 predatory animals, together with an identification sheet compatible with the IDgis program, are noticed. The small secure box will make a 15 € product, showing that the buyer has good intentions. A problem that can occur is that the product itself is cheap, so customers do not believe in its effectiveness (Flinn *et al*., 2015) [33]. Furthermore, it is important to raise awareness among people who will buy goods to recognize harmful and beneficial organisms because it is known that many EU citizens are unnecessarily afraid of insects and other organisms in stored products (Isman, 2020) [43]. On the other hand, it may be expected that pesticides in storage places will not be sufficiently active after a longer period of storage, and that the use of such goods will be dangerous to one's health (Nayak *et al*., 2020) [68]. It will probably be necessary to find a new way of treating the space into which the goods are stored that will not need to be repeated, on the one hand, active for a long time, on the other not dangerous for end customers (Hamel *et al*., 2020) [36, 37].

**Real-World Applications of Innovative Technologies**

During the last decade, innovative technologies based on physical modification of storage structures or natural biological control have been designed to address insect resistance to phosphine fumigation (Nayak *et al*., 2020) [68]. There is an opportunity to review real-world adoption of these approaches to reduce losses, particularly in developing nations where losses exceed 50% and grain treatment could enhance food security (FAO, 2020) [30]. Recent journal articles on innovative pest control technologies analyze short-term investment options, with the most pertinent paper providing a global-scale foundation for reviewing new strategies (Athanassiou *et al*., 2022) [4, 5].

A major barrier to industrial-scale natural pest control is the lack of cost-effective, automated mass production methods for biological agents. SLPE and DIACON technologies produce no harmful by-products, making them safe alternatives to chemical fumigation, especially in underdeveloped regions (Perkin *et al*., 2016) [73, 74]. Storage bin treatments combine kaolinite, diatomaceous earth, and insecticidal/fungicidal powders (Subramanyam & Roesli, 2020) [89]. Solar-powered inflatable disinfestation devices are designed for rural facilities (Navarro, 2016) [65, 66]. SLPE technology is expected to dominate markets for natural grain protectants (Perkin *et al*., 2016) [73, 74].



## Conclusion
The escalating challenge of storage pest infestations, exacerbated by global trade and climate change, demands a paradigm shift from reliance on synthetic chemicals to sustainable, integrated solutions. This review underscores the limitations of conventional pesticides—notably pest resistance, environmental contamination, and health risks—while highlighting the potential of emerging strategies such as entomopathogenic fungi, botanical essential oils, and diatomaceous earth (DE). These alternatives align with ecological sustainability, offering targeted efficacy without compromising food safety or non-target organisms. For instance, entomopathogenic fungi like *Beauveria bassiana* exploit pests' biological vulnerabilities, while thyme oil and DE disrupt insect physiology through physical and biochemical mechanisms. Complementing these, advancements in nanotechnology and IoT-enabled monitoring systems promise precision control through real-time data analytics and automated interventions, reducing dependency on broad-spectrum chemicals.

However, challenges persist. Phosphine resistance in pests like *Rhyzopertha dominica* threatens global grain security, necessitating resistance management protocols and novel fumigation alternatives. Regulatory barriers and scalability issues further hinder the adoption of biopesticides, while consumer skepticism toward biocontrol agents underscores the need for education and standardization. Integrated Pest Management (IPM) emerges as a critical framework, harmonizing biological, physical, and chemical tactics to enhance resilience. For example, combining pheromone traps with fungal treatments or modified atmospheres (e.g., $CO_2$ enrichment) can suppress pest populations synergistically.

Looking ahead, interdisciplinary innovation is vital. Genetic tools like RNA interference (RNAi) and CRISPR could revolutionize pest-specific targeting, while blockchain-enabled traceability systems may strengthen supply chain accountability. Global collaboration to standardize storage protocols and incentivize green technologies will be pivotal in mitigating postharvest losses, which currently undermine food security for millions. Ultimately, the transition to eco-centric pest management is not merely a technical necessity but a moral imperative, ensuring equitable access to safe food and safeguarding ecosystems for future generations. By bridging traditional knowledge with cutting-edge science, the agricultural sector can cultivate a resilient, sustainable future in the face of evolving pest threats.

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