OPEN ACCESS Plant Protection, 08 (02) 2024. 351-363 DOI:10.33804/pp.008.02.5154

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Available Online at EScience Press
Plant Protection
ISSN: 2617-1287 (Online), 2617-1279 (Print)
http://esciencepress.net/journals/PP

Review Article

IMPLEMENTATION OF ENVIRONMENTALLY FRIENDLY METHODS FOR THE MANAGEMENT OF STORED PRODUCT INSECTS

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ARTICLE INFO

Article history
Received: 6th April, 2024
Revised: 23rd May, 2024
Accepted: 28th May, 2024

Keywords
Biological control of stored insects
Food safety in storage
biorational methods
Stored product pests

ABSTRACT

Postharvest losses can be caused by insects infesting stored products, with estimates ranging from up to 9% in industrialized countries to 20% or more in underdeveloped ones. Due to the potential harm of insecticides, including regulatory restrictions and insect resistance, as well as the increasing consumer demand for insect-free and insecticide-free products, there is significant interest in developing alternatives to traditional insecticides for eliminating insects in stored products. Sanitation may be the first line of defense for stored grain, as well as for food processing companies and warehouse operations. For farm-stored grain, manipulating temperature and utilizing biological control are two of the most promising biologically derived management strategies. Various biologically derived methods for protecting stored plant products against infestation are currently recognized and partially employed. However, these techniques require further refinement to enhance their efficacy in practical applications. This involves the use of semiochemicals to monitor and regulate pest populations and the introduction of natural enemies (namely parasitoids) as biological control agents for stored-product pests. Some modern techniques can be implemented in grain elevators. In this article, we review the biologically derived substances that have proven successful in managing stored product insects.

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INTRODUCTION

Worldwide, stored-product insects pose a major problem, consuming a wide variety of agricultural goods, both food and nonfood, those have been dried and kept for an extended period. Postharvest losses due to stored-product insects can be substantial; reaching 20% or more in underdeveloped nations and around 10% in industrialized ones (Pimentel, 2019). Live insects, chemical excretions, silk, dead insects, parts of their bodies, infestation of buildings and storage facilities, and chemical insecticide residues in food all contribute to the danger of food contamination these pests represent (Pimentel, 2019). There are numerous safe and effective alternatives to pesticides for managing stored-product insect pests.

There has been a long history of connecting human activity with stored-product insects, with methods for diagnosis and control documented for more than a century (Levinson and Levinson, 1985). Current stored-product Integrated Pest Management (IPM) research is driven by pioneers in the field, and government regulations, customer expectations, and business needs drive urgent goals. IPM is a holistic and proactive approach designed to safeguard stored agricultural products across the entire supply chain, from production to consumption. IPM begins at harvest and continues until the grain reaches consumers. It involves employing preventive measures to preserve grain quality and prevent insect infestation. It also includes using monitoring tools and strategies to identify when corrective actions are necessary. Additionally, there are management tools available to control infestations caused by insects present in stored products. Utilizing physical, mechanical, and chemical techniques to manage, prevent, and control stored grain is crucial for achieving success in IPM in bulk storage and processing facilities, ultimately leading to favorable outcomes in the marketplace. The conventional goals are to store grain and food safely without insect or pesticide damage. Research on chemical-free or biologically based stored product pest control has been encouraged and funded. This review covers basic literature and updates on recent literature, focusing on biologically based approaches with proven efficacy, legal registration, and potential commercial adoption in the grain, food, and pest control industries.

IMPORTANCE OF STORED PRODUCT INSECTS AND THE COMMON CONTROL METHODS

Pests can cause significant losses both before and after harvest (Pimentel, 2019; Alshabar et al., 2021; Adhab and Alkuwaiti, 2022; Khalaf et al., 2023). This can lead to a reduction in crop yield and quality, and in some cases, the complete loss of the crop (Adhab et al., 2021). Post-harvest losses occur when pests infest stored crops, causing damage and spoilage. The storage of agricultural and animal products is subject to attack by more than 355 species of mites, 70 species of moths, and 600 species of beetles, leading to both quantitative and qualitative losses (Rajendran, 2002). One of the biggest problems with food quality management is the presence of bugs in meals. Industrialized countries such as Australia and Canada have outlawed food grains that include insects (White, 1995; Pheloung and Macbeth, 2002). To keep stored products free of insects, fumigation is a must. Methyl bromide (in metal cans and cylinders) and phosphine are the two most common fumigants used to preserve stored products globally. Some countries have experienced problems in the field due to phosphate-resistant insects, which is a worldwide problem (Hassan et al., 2021). The ozone-depleting effects of the broad-spectrum fumigant methyl bromide have led to its gradual elimination from use. Because of the problems with current fumigants, there is a worldwide push to find chemical alternatives, implement controlled environments, and combine physical methods (Deguine et al., 2021).

U.S., Canadian, and European flour mills, among others, use sulphur fluoride, a structural fumigant for termite and woodborer management (Prabhakaran, 2006). Carbonyl sulfide, ethane dinitrile, and ethyl formate have all been investigated as potential substitutes for both food and non-food goods. Because of their local availability, quick disintegration, and minimal mammalian toxicity, plant products (including essential oils and their components) may be superior fumigants to traditional ones (Falah and Azher, 2020a; Ali and Sabit, 2023). Depending on the plant extract, insects can be poisoned, deterred from feeding, killed, or repelled (Nawrot and Harmatha, 1994; Isman, 2006; Adhab et al., 2019). Toxic effects might manifest as fumigant, ingestion, or contact poisoning. The toxicity of plant essential oils and their components as fumigants or vapors has grown significantly since the 1980s (Baazeem et al., 2022). Essential oils and monoterpenoids are among the plant products that have been studied for their effectiveness against stored product insect pests and farm pests in numerous publications (Rajendran and Sriranjini, 2008; Al-Ani et al., 2011a,b,c, 2013; Ali and Sabit, 2023). Fumigants kill pests in the air, including low-boiling chemicals like methyl bromide and sulphuryl fluoride and volatile compounds like naphthalene, paradichlorobenzene, and chloropicrin, which affect insects in gaseous or vapor form (Rajendran and Sriranjini, 2008).

HEALTHY PRACTICES AND ENVIRONMENTAL MAINTENANCE IN STORAGE FACILITIES TO REDUCE LOSSES

Effective exclusion of stored-product insects from structures and food packaging, along with thorough cleaning of grain and food storage facilities, is essential for preventing storage pests. Freshly harvested grains should be stored in insect-free bins, separate from older grains. Prior to harvesting and storing new crops, it is necessary to clean all harvesting equipment, containers, loading sites, and storage bins. To eliminate any lingering insects, treat the interior walls, floors, and ceilings of storage areas with residual insecticides (Kumar and Kalita, 2017; Yasir et al., 2020). Thus, mechanical, electrical, and structural engineering must be considered in developing and maintaining product-storing structures and bins (Al-Ani and Sadoon, 2023; Anaz et al., 2023). Bins housing unprocessed grains should be kept separate from processing areas and farther away from warehouses or loading areas for finished products and packaging in food processing facilities, as these grains can be stored for months and may harbor stored-product insects.

Because lights can attract a wide variety of insects, including stored-product insects (Park and Lee, 2017), they should be placed on poles to illuminate buildings directly rather than near exterior entrances. Proper functioning of window screens and doors, especially those connecting bulk storage, warehousing, and processing areas, is crucial in preventing the movement of insect pests. Everything needs to be easily accessible for cleaning. Instead of blowing food debris into hard-to-reach places like beams and ledges, large processing factories should sweep and/or vacuum all debris to eradicate any trace of food.

To keep insects out of processing facilities, storage bins, and finished food packaging, certain precautions can be taken. To avoid pest infestation, water damage, and mold growth caused by rain leaks, ensure the top and sides of storage bins are sealed. Proper bin sealing is required for the use of chemical fumigants. Underfloor intake aeration vents and ceiling ventilation must be covered with insect-proof screening and shut during fumigation to control grain moisture and temperature (Casada and Noyes, 2001). Food packaging, whether for wholesale or retail sale, must be impenetrable to postharvest insect pests (Mullen et al., 2012).

Insects that feed on stored goods often target food containers by chewing through and penetrating the packaging material or by finding cracks or other weak spots in the seal (Vincent et al., 2003). Food packaging needs to be sturdy and tightly sealed to prevent insect entry. Although technologies to impregnate packaging with low-risk insecticides and insect repellents have been developed, their commercial use is limited by low cost-effectiveness and public acceptance (Hou et al., 2004).

a. Reducing losses by manipulating storage temperature

Changing the temperature of the surrounding environment is one method for controlling insect populations. Most insects are most active between 25 and 33°C, become disabled at temperatures much higher or lower, and perish between 13 and 35°C (Jian, 2024). Unlike American concrete silos and flat storages, steel bins use aeration to cool grain and inhibit insect population growth.

For a long time, mills have used heat to destroy insects (Paul et al., 2020; WHO, 2021). Since methyl bromide is no longer available, heat is becoming the preferred treatment for insect infestations. The entire plant or specific trouble spots can be heated. To successfully control insects, it is recommended to raise the mill temperature to 50-60°C for a day (Gerken and Campbell, 2022). Fans are useful for heat disinfestation because they maintain a consistent temperature.

Aeration is a widespread practice in China for ventilating vast government-owned flat storages. It can be beneficial for crops harvested in the summer, as it can lower grain temperatures by 3 to 4°C when aeration fans are operated at night. However, studies on using aeration during the summer to manage grain insects in the United States have yielded inconsistent findings (Arthur and Casada, 2005). Summer aeration had a variable impact on insect populations, decreasing them in some years while not affecting them in others (Arthur and Casada, 2005). This may be because summer aeration reduces temperatures near the grain surface, where insects are commonly found, from fatal values of 40°C in warm areas to more favorable levels for insects.

Aeration is a viable method for controlling pests in crops stored during the fall in regions with cold weather. It can be used in conjunction with other control measures, such as chemical or biological control. However, heat disinfestation has the potential to damage older structures and heat-sensitive machinery, which is a concern for food industry sanitarians (Fields and White, 2002).

b. Methods to reduce storage losses

A biorational alternative to chemical fumigation, exposing insects to toxic air gases has been practiced for millennia (Navarro and Navarro, 2020). While a modified atmosphere subtly shifts gases from a tolerable level to one that is dangerous, a controlled environment keeps gas concentrations at a target level. Insect-toxic gas concentrations are 3% oxygen and 60% carbon dioxide.

Humidity control is another method of managing stored product pests (Falah and Azher, 2020b). Since most grain-feeding insects thrive at 12-18% moisture

(Deshwal et al., 2020), reducing moisture levels is an effective pest control measure. Wheat stored in bins with 7% moisture has minimal insect problems due to low-moisture grain and low harvest temperatures in the far northern US and Canada. However, grain kernels can be shattered during drying (Montross et al., 1999), making them more vulnerable to insects. Insect control via artificial drying has been uncommon.

One study found that using a pneumatic conveyor to shift grain killed 70-100% of adult and larval beetle pests (Suleiman and Rosentrater, 2022). Elevators typically turn grain to inject phosphine fumigant, chill it, or kill insects; farm storages rarely turn grain. Grain can become more insect-friendly when broken during movement. Controlled field tests have not found cost-effectiveness in using sieving or scalping to remove broken material from grain to minimize populations of external-feeding insects (Flinn et al., 1993). Although commonly used in flour mills to eliminate flour-borne insects (Draz et al., 2021), entoleters (impact machines) also break down whole grains and coarse-grained products.

Radiation from gamma rays or other ionizing sources can be used to irradiate long-term storage products in most nations, while radiation from radio waves, microwaves, or infrared rays can heat the product or insects through the vibration of water molecules (Rajendran, 2020). Irradiation can disinfest grain entering a storage facility or remediate infested grain. Building air and surfaces, as well as tolerant commodities, can be heated using infrared irradiation. Insects and nearby commodities can be heated to the point of cell breakdown and death through microwaves and radio frequencies. However, these techniques cannot be applied to entire structures; they need to be done in a thin layer per kernel. Commercial implementation would require significantly increased grain production and would be prohibitively expensive. However, a pilot-scale experiment found that high-energy microwaves killed insects without affecting grain quality (Phillips et al., 2003).

BIOLOGICALLY BASED CONTROLS

a. Pheromones and other semiochemicals

Over 40 species of stored-product insects have been reported to possess semiochemicals, including attractant pheromones (Morrison et al., 2021). Insects that store their food use two primary pheromone systems according to their life cycles. Non-feeding, short-lived insects utilize sex pheromones released by females to “call” and mate. Males respond upwind to the attractant chemicals released by a receptive female. Beetles of the Anobiidae, Bruchidae, and Dermestidae families, as well as stored-product moths of the Pyralidae subfamily Phycitinae, use a sex pheromone system. Tineidae clothing moth males release resource-based pheromones, such as where larvae feed (Takacs et al., 2002), while females produce pheromones that attract males (Takacs et al., 2001).

Beetles attract both sexes using aggregation pheromones produced by males. Beetles, which are long-lived and feeding adults, forage for food, produce pheromones, mate, and attract both females and other males, who then lay their eggs and raise their larvae in the same location. The Tenebrionidae, Cucujidae, and Curculionidae families use aggregation pheromone systems and feed on stored products (Currie et al., 2020; Doud and Phillips, 2020; Ponce et al., 2021; Campbell et al., 2022). Pheromone traps are highly specific to particular species and can identify insects, unlike many conventional sampling methods. For 23 different kinds of stored-product insects, monitoring traps with slow-release lures are available (Subramanyam and Hagstrum, 2000). Some of the most popular pheromones include those for *P. interpunctella*, *Lasioderma serricorne* (F.), *Tribolium castaneum*, *T. confusum* Jacquelin du Val, and *Trogoderma variabile* Ballion, all belonging to the Coleoptera: Anobiidae family.

Sticky traps baited with pheromones are more effective at capturing male of *P. interpunctella* when they settle on other flat surfaces (Nansen et al., 2004). Insect traps are designed to lie on flat surfaces like floors and catch insects that walk into them. The insects either stick to the surface or get entangled in the trap. A study by Barak and Burkholder (1985) found that corrugated cardboard layers laid out horizontally could capture beetles in a trap by leading them through tunnels to a cup of oil. Another design, the ramp-and-pitfall trap, allows beetles to climb an inclined edge and fall into an oil container (Sajeewani et al., 2020). Oil is used as a medium for capturing insects and as an additional attractant or pheromone synergist in several floor traps created from grain (Phillips et al., 2001). Using kairomones from larval meals, researchers attracted female *P. interpunctella* and other stored-product moths (Sambaraju and Phillips, 2008).

In value-added food systems, attractive traps can aid in

IPM when used correctly. Pest species can be detected using pheromone traps, and data collected from trap captures over time and space in a facility helps in monitoring. While pheromone traps are not as useful as direct and indirect sampling when dealing with bulk grains, high numbers of trap captures may indicate more pests in the grain if aggregation pheromones attract female pest insects. Warehouses and processing plants for food should distribute traps cost-effectively and evenly across the target area. Insect inspections of traps should be done frequently, such as once every two weeks, year-round. Spatial analysis and geographic information tools can help illustrate where pest insects or infestations are most likely to occur in a building using trapping data (Nansen et al., 2003, 2008). However, pest managers may also find it useful to manually observe the data collected over time, generally catching populations in samples. Management should monitor insect numbers in traps at different places and compare them to historical sample timings. Pheromone traps can be used to determine the effectiveness of management by comparing captures taken before and after fumigation or heat treatment (Rajendran, 2020).

Pheromones can help manage pest insects that feed on stored goods. If enough males are removed from a population, sex pheromone-trapped males may theoretically control it (van Herk and Vernon, 2023). Male moths like *P. interpunctella* can maintain a reproductive rate comparable to populations not subjected to mass trapping if there are a small number of them, as they can inseminate six females during their lifespan. Despite the challenges, mass-trapping of storage moths has been documented in retail food storage in the US (Campos-Figueroa, 2008) and Europe (Subramanyam and Hagstrum, 2000). The attract-and-kill method involves luring male moths with a pheromone before they die upon brief contact with an insecticide-treated surface, eliminating the need to maintain traps that can become overcrowded with dead moths. Under controlled conditions, mating disruption is effective for stored-product moths (Sammani et al., 2020) and has recently shown promise in commercial field settings (Hasan et al., 2023), where an abnormally high quantity of synthetic sex pheromone prevents males from finding and mating with females.

In the US, pheromones used for pest control of insects must be registered with the government. A synthetic sex pheromone for stored-product moths, Z,E-9,12-tetradecadienyl acetate, was fully registered. This pheromone is useful for controlling stored-product moths with grains and food because it acts as an insecticide and does not establish banned residue levels for exposed foods (Levi-Zada and Byers, 2021). There has been no prior licensing of a sex pheromone to interfere with mating in the United States.

b. Natural enemies in stored product insect management

The natural enemies of stored-product insects are highly adaptable to human environments, much like their prey and hosts. Some Pteromalidae wasps are solitary parasites that live externally on grain-infesting beetles that feed internally. Additionally, certain species of Ichneumonidae and Braconidae are parasites that inhabit both the external and internal regions of stored-product Lepidoptera. Carnivorous beetles, Minute Pirate Bugs (Heteroptera: Anthocoridae), and mites are free-roaming predators capable of overpowering and consuming various insect pests found in stored products, regardless of their developmental stage. Parasitoids and predators in storage systems exhibit delayed density dependence, similar to what is observed in other insect communities. Reductions in populations of pests infesting stored products often coincide with corresponding increases in populations of natural predators or parasites.

In accordance with regulations set by the FDA (U.S. Food and Drug Administration) and EPA (The United States Environmental Protection Agency), insect parasitoids and predators are permitted for introduction into large-scale grain and food storage facilities in the United States (Anonymous, 1992). Insect natural enemies are categorized as pesticides and are exempt from the need to meet food tolerance requirements. The FDA's regulation on food contamination limits the presence of insect fragments in processed goods like bread flour, making it legally impossible to exceed the allowed level since distinguishing between pest insects and fragments of their natural predators is not feasible.

These regulations allow the integration of insect predators into stored-product systems and enable pest managers to implement pest control methods based on biological principles. While commercial sources for natural enemies to control pests in stored products are limited, there have been successful small-scale efforts indicating potential (Rajendran, 2020).

c. Microbial insecticides for stored product insects

Due to a lack of broad-spectrum activity, none of the insect diseases studied for controlling stored-product insects are routinely used. Insects may be more vulnerable to infections when used in conjunction with other control strategies, such as diatomaceous earth (DE) to abrade the cuticle or grain varietal resistance to delay larval development (Gad et al., 2021; Pourian and Alizadeh, 2021). Both the fungi *Beauveria bassiana* and *Metarhizium anisopliae*, which are commercially available, and the bacterium *Bacillus thuringiensis* (Bt), whether used alone or with DE, tend to control only part of the life cycle of some species, while other species show inadequate control in laboratory experiments (Javed et al., 2019; Gad et al., 2021; Pourian and Alizadeh, 2021; Shehzad et al., 2021, 2022; Elsharkawy et. al., 2022). Although various strains of Bt work better against beetles, most Bt is effective against diptera and lepidoptera (Elsharkawy, 2022). While pathogenic pesticides have been effective against agricultural pests in the field (Al-Ani et al., 2012, 2013; Al-Ani and Adhab, 2013), commercial use of pathogens against stored-product insects is limited due to low efficacy. Despite being registered for decades to manage stored-product Lepidoptera, Bt is rarely used since it does not control beetles. Commercial application has been limited despite the successful description of *Plodia interpunctella* and its natural *granulosis virus* (PiGV) and a low-cost mass-production technology (Rajendran, 2020).

The insecticide spinosad is produced via the fermentation of metabolites by the actinomycete bacterium *Saccharopolyspora spinosa* (Chio and Li, 2022). The United States Environmental Protection Agency (Anonymous, 2005) has verified that conventional and organic formulations of spinosad, with a residue tolerance of 1.5 ppm, are safe for use on stored grain. However, spinosad has not been distributed by the manufacturer yet because not all of the US's international trade partners have fully approved the tolerance limits on stored grain, as required by the Codex Alimentarius (international food safety regulations). Because *R. dominica* is the most common pest of stored wheat, and other residual insecticides authorized in the US and worldwide are either ineffective or face resistance issues, the use of spinosad on stored grain is an intriguing prospect. Seasonally, spinosad suppresses *R. dominica* in stored wheat. It is compatible with natural enemies of insects and toxic to various stored-product insect larvae (Perišić et al., 2022; Vassilakos and Athanassiou, 2023).

d. Potential of botanical insecticides in the management of stored product insects

While there is a lot of research on the topic of pest control using plant extracts or whole plants, there have been very few practical applications (Rajandran, 2020). Farmers in developing countries often use natural or homegrown plant materials as pesticides. There are concerns about the uniformity, safety, and odor of botanical pesticides. Many people mistakenly believe that plant extracts used in culinary or medicinal applications are completely safe to consume.

One common method for controlling insects in stored products in some areas is the use of neem pesticides, which are botanical insecticides derived from the *Azadirachta indica* tree (Rajandran, 2020). However, over-the-counter remedies have only a modest impact (Kavallieratos et al., 2007). Peas (*Pisum* spp.), crude pea flour, and other protein-rich edible legumes (e.g., *Pisum, Phaseolus*, and *Vigna*) are toxic to and repel stored-product insects (Fields, 2006). Reportedly, stored-grain beetle populations were reduced by directly applying protein-enriched pea flour to bulk grain at a weight of 0.1% and by applying pea flour to mill interiors on a large scale. However, the levels of control were not commercially viable, unlike synthetic fumigants.

Perhaps the most powerful plant pesticide in use today is pyrethrum, a commercial mixture of components from *Chrysanthemum cinerariifolium* and additives. Pyrethrum contains pyrethrins. Synergized pyrethrum, which includes piperonyl butoxide (PBO), decreases the insect metabolism of pyrethrins. Due to its short-lived effectiveness, synergized pyrethrum is typically mixed with a longer-acting insecticide for aerosol application in flour mills (Toews et al., 2006). Recently, an organically compliant pyrethrum has been registered in the US. It is extracted from chrysanthemum flowers using methods approved by the USDA National Organic Program. This pyrethrum may be able to manage stored-product insects.

e. Application of insect growth regulators (IGRs)

Insect juvenile hormone analogs such as methoprene, hydroprene, and pyriproxyfen are used in stored product systems in the United States and various other countries (Rajandran, 2020). These substances affect the growth of larval instars and the transition from larvae to pupae and then to adults, effectively imitating the prolonged hormone titer of insects in their juvenile stages. Although the effects of these IGRs on reproductive sterility are unknown, they pose no danger to humans. Other advantages of these IGRs include high levels of food safety and minimal mammalian toxicity. Methoprene was exempted from a tolerance by the United States Environmental Protection Agency due to its non-toxicity (Anonymous, 2003). Methoprene has a lethal dose (LD50) of more than 34,500 mg/kg in rats (O'Neil, 2013). When treated with 1 ppm methoprene, stored grain can maintain its insecticidal activity for more than a year because the grain is protected from UV radiation and temperature fluctuations.

Hydroprene, an isomer of methoprene with slightly higher volatility, is used more effectively as an aerosol in space treatments because it can penetrate gaps and untreated areas. Pyriproxyfen, a structurally different chemical, performs better than hydroprene in terms of residual action duration on various surfaces (Arthur et al., 2009). Compared to residual contact insecticides and fumigants, IGRs for grain storage are both safe and effective; however, their widespread application has been hindered by the high cost of these products and their inability to provide a rapid knockdown.

IGRs are frequently used for aerosol treatment of food processing and finished product storage facilities, especially when combined with pyrethrum or dichlorvos to eliminate insect life stages instantly. The use of IGRs may have increased due to pest management efforts to find alternatives to methyl bromide. Within the food industry, low-risk biological pesticides such as IGRs have the potential to gain popularity. However, IGRs cannot be used in organic production because they are synthetic.

f. Resistant crops and foods safely reduce storage losses

Since the 1970s, the use of inexpensive pesticides like malathion has significantly replaced varietal resistance as a method for managing stored-product insects in the United States. Although pest resistance is considered when developing new crop varieties (Chuang et al., 2017; Adhab et al., 2018, 2019), the resistance of stored products to pests is often overlooked. Despite this, the insect resistance of commercial crops varies greatly from one crop to another. The integrity of the rice hull is the most accurate predictor of rice resistance to *R. dominica* (Astuti et al., 2021). Resistance to *Sitophilus zeamais* and *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in corn is associated with its phenolic content, which can affect kernel hardness (Arnason et al., 1992). Similarly, hull integrity, endosperm hardness, and thickness in sorghum are linked to its resistance to storage insects (Khalaf et al., 2019; Subramanyam and Hagstrum, 2000). The reasons for the varying degrees of wheat resistance to insects that feed on stored products remain unknown (Subramanyam and Hagstrum, 2000). Some oat cultivars grown in the United States are nearly immune to storage insect pests (Throne et al., 2003), though the resistance mechanism is still unclear.

With the exception of *P. truncatus*, transgenic avidin maize, which is grown to harvest avidin for medical research, is resistant to all storage insect pests (Kramer et al., 2000). Avidin binds biotin, which results in the death of insects. Regarding storage insects, two Bt transgenic rice lines containing cry1Aa and cry1B genes for *Chilo suppressalis* Walker showed a range of nontarget effects (Riudavets et al., 2006). *P. interpunctella* did not survive on semolina from either line, and the production of progeny from *S. oryzae* and *Liposcelis bostrychophila* (Badonnel) (Psocoptera: Liposcelididae) was reduced on one line.

CONCLUSION

Adopting environmentally friendly measures is essential in combating stored product insects. Eco-friendly methods in stored product insect control are crucial for protecting the environment, ensuring human health, achieving economic sustainability, complying with regulations, and maintaining the long-term efficacy of pest management strategies. These methods represent a responsible approach to managing pest issues sustainably and beneficially for both current and future generations. Stored product insects can cause substantial harm to food supplies, resulting in financial losses and food shortages.

A recent analysis has found that biorational methods, including sanitation, temperature management, natural enemies of storage pests, computer-assisted decision-making systems for pest control, and insect sampling, are effective in managing stored product insects. Furthermore, plant-based insecticides, such as essential oils and their bioactive ingredients, have been found to effectively combat storage insect pests. These chemicals work by inhibiting acetylcholinesterase activity, modifying the receptors for octopamine and γ-amino butyric acid, and altering the enzymatic and non-enzymatic antioxidant defense systems.

However, there are still challenges associated with the commercialization of these substances, such as their effectiveness in actual food systems, accessibility, standardization, toxicological assessment, evaluation of their impact on non-target organisms, limited duration of their effects, and regulatory authorization. It is crucial to acknowledge that enhanced plant resistance can simultaneously reduce the occurrence and detrimental impacts of insects. Therefore, embracing environmentally sustainable methods is imperative to effectively control stored product insects and safeguard food security.

FUTURE DIRECTIONS

Additional research is needed to determine the economic viability of using cleaning as a management strategy for stored grain to control the proliferation of external-feeding insect pests, specifically. Furthermore, economic and pest management studies should assess the effectiveness and cost-efficiency of using insect exclusion as a method for managing grain storages.

Further study is necessary to interpret trap capture data in both stored grain and processing facilities, aiding in informed decisions on pest management. Additionally, ongoing advancements are needed in automating the collection and utilization of trap count data. Commercial sources also need to acquire biological control agents for combating stored-product insects.

Research in molecular biology and genetics is essential for creating insect-resistant stored grains that are safe for human consumption. Additionally, producing biopesticides that target stored product insect pests while being ecologically friendly and suitable for use in food and animal feed is crucial.

Research efforts should also explore techniques for decontaminating and preserving organic goods, such as maximizing the efficacy of freezing.

AUTHOR’S CONTRIBUTION

The author collected, sorted out, and arranged the literature into different sections, drew conclusions, made suggestions for future directions, and wrote and proofread the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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