***Review Article***

**Recent Advances in Stored Product Pest Management Through Eco Friendly Technologies and Monitoring Tools- A review**

**Abstract**

Stored product pests cause significant post-harvest losses globally, threatening food security, grain quality, and economic returns. Conventional control methods, predominantly reliant on chemical fumigants and insecticides such as phosphine and methyl bromide, have raised concerns due to pesticide resistance, environmental contamination, and human health hazards. In response, recent advancements emphasize the development and implementation of eco-friendly pest management technologies and advanced monitoring tools within the framework of Integrated Pest Management (IPM). Botanical pesticides, including essential oils and plant extracts, have demonstrated insecticidal and repellent properties with reduced ecological footprint. Biological control agents, such as *Beauveria bassiana*, *Metarhizium anisopliae*, and parasitoids like *Anisopteromalus calandrae*, offer species-specific suppression of pest populations. Physical methods including modified atmospheres, temperature treatments, and inert dusts provide non-residual, safe control options. Simultaneously, innovations in pest monitoring through pheromone-based traps, electronic sensors, IoT-enabled smart systems, spectroscopy, and molecular diagnostics have enabled early detection, precise intervention, and resistance monitoring. These tools enhance IPM efficiency by integrating surveillance with targeted action. National and international regulatory frameworks now promote reduced pesticide dependency and support the adoption of safer alternatives. Despite these advancements, challenges persist, such as variability in field efficacy, limited access to eco-friendly products, and the need for training among stakeholders. Cost-benefit analyses show that green technologies, though sometimes requiring higher initial investment, provide long-term economic and environmental gains. Market trends reflect growing consumer demand for residue-free commodities, further encouraging sustainable storage practices. Continued research, technology standardization, and public-private collaboration are essential to overcoming existing barriers. Synthesizes recent developments in environmentally safe pest control strategies and monitoring tools for stored product protection, highlighting their potential to replace hazardous chemicals, enhance grain quality, and support global food safety objectives through sustainable storage management solutions.

**Keywords:** *Pest, Storage, Botanical, Biological, Monitoring, IPM, Sustainability*

**II. Introduction**

***A. Stored product pests and global food security***

Stored product pests pose a significant threat to post-harvest agricultural commodities. Globally, these pests cause substantial qualitative and quantitative losses to food grains, pulses, oilseeds, and other stored products (Yaseen *et.al.,* 2019). More than 600 species of insects are known to infest stored products, among which beetles (Coleoptera) and moths (Lepidoptera) are the most prominent. Common pests such as *Sitophilus oryzae* (rice weevil), *Tribolium castaneum* (red flour beetle), and *Plodia interpunctella* (Indian meal moth) lead to direct consumption of grains and contamination through feces, exuviae, and webbing. The issue of post-harvest losses due to insect pests is closely linked to global food security. According to the Food and Agriculture Organization (FAO), post-harvest losses can range from 10–30% in developing countries, contributing significantly to food insecurity. Reducing such losses through efficient pest management is considered a critical component in achieving the Zero Hunger goal (SDG 2) of the United Nations Sustainable Development Goals (Arora *et.al.,* 2022).

***B. Economic losses and health risks associated with infestation***

Infestation of stored grains leads to significant economic losses both at the farm and industrial levels (Upadhyay *et.al.,* 2011). Worldwide, the value of food lost due to insect infestation during storage is estimated to exceed billions of US dollars annually. In the Sub-Saharan region, it has been reported that maize losses due to pests like *Prostephanus truncatus* can exceed 30% within 3–6 months of storage. Besides direct losses, contaminated grains have reduced market value, leading to export rejection and consumer dissatisfaction. Contaminants such as insect fragments, webbing, and microbial byproducts pose serious health hazards. Mycotoxins, produced as secondary metabolites by fungi that thrive in pest-damaged grains, are known to cause carcinogenic, nephrotoxic, and immunosuppressive effects in humans and animals. Aflatoxins and ochratoxins are of particular concern in commodities like maize, peanuts, and cereals.

***C. Limitations of conventional pest management methods***

Historically, pest management in stored commodities has relied heavily on chemical fumigants and contact insecticides (Hagstrum *et.al.,* 2017). Commonly used fumigants include phosphine and methyl bromide. Although effective, these chemicals present numerous limitations. Methyl bromide, for instance, has been phased out under the Montreal Protocol due to its ozone-depleting properties. Phosphine, while still widely used, is increasingly facing resistance development among key pests such as *Tribolium castaneum* and *Rhyzopertha dominica*. Contact insecticides, such as malathion and deltamethrin, leave residues that raise concerns regarding food safety, worker exposure, and non-target effects. The overuse and misapplication of these chemicals accelerate resistance, leading to reduced efficacy and the need for higher doses, which exacerbates environmental contamination and human health risks (Zhou *et.al.,* 2024).

***D. Rationale for shifting toward eco-friendly and sustainable approaches***

The limitations of chemical-based control strategies have led to a growing interest in developing and implementing environmentally sustainable alternatives. These alternatives include botanical insecticides, biological control agents, physical methods, and integrated pest management (IPM) strategies that aim to reduce reliance on synthetic chemicals. Consumer preference for residue-free products, along with stricter international regulations on pesticide residues in food commodities, is driving the adoption of safer pest control measures. Research has shown that certain essential oils and plant-derived compounds exhibit insecticidal and repellent properties while being biodegradable and safe to humans. Biological control agents, such as entomopathogenic fungi and parasitoids, offer targeted pest suppression without harming non-target organisms or leaving harmful residues (Singh *et.al.,* 2017).

**III. Major Stored Product Pests**

***A. Insect pests***

Stored product insects are the most common and destructive pests responsible for considerable quantitative and qualitative losses in stored food commodities (Srivastava *et.al.,* 2016). These insects infest grains, flour, dried fruits, nuts, and other dry food products, leading to contamination and reduction in nutritional and commercial value.

***1. Coleoptera (e.g., Sitophilus spp., Tribolium spp.)***

Beetles from the order Coleoptera comprise the largest and most economically significant group of stored product pests. Among them, *Sitophilus spp.* (grain weevils) and *Tribolium spp.* (flour beetles) are extensively reported across warehouses and storage systems worldwide. *Sitophilus oryzae*, *S. zeamais*, and *S. granarius* are internal feeders that bore into whole grains to lay eggs, making early detection difficult. Larval feeding within the kernel causes severe internal damage, resulting in substantial weight loss, decreased germination, and visible frass accumulation (Labella *et.al.,* 2024). It has been estimated that *Sitophilus* spp. alone can lead to losses of up to 30% of stored grains within 3–6 months under favorable conditions. *Tribolium castaneum* and *T. confusum* are external feeders and known secondary colonizers. These beetles infest milled products, processed foods, and cracked grains. The secretion of quinones by *Tribolium* beetles taints food products with an unpleasant odor and flavor, contributing to product rejection. A single female *T. castaneum* can lay 300–500 eggs during her lifespan, leading to rapid population build-up under warm and humid conditions.

***2. Lepidoptera (e.g., Plodia interpunctella)***

The Indian meal moth, *Plodia interpunctella*, is a cosmopolitan pest that infests a wide range of stored commodities, including grains, cereals, dried fruits, nuts, and chocolate (Mohandass *et.al.,* 2007). Larvae spin silken webs across food surfaces, contaminating products with excreta and exuviae, making them unfit for consumption. Female moths lay 100–400 eggs during their short adult life. Larval development is influenced by temperature and humidity, with development completing within 25–30 days under optimal conditions. The ability of *P. interpunctella* to infest both raw and processed foods, combined with its resistance to certain fumigants, makes it a particularly difficult pest to manage (Grains *et.al.,* 2012).

***B. Mites and rodents***

Stored product mites, such as *Acarus siro* and *Tyrophagus putrescentiae*, thrive in high-moisture environments and can be found in grains, flour, and oilseeds. Their presence leads to clumping, discoloration, and the generation of allergens and off-odors. Mite infestations are also linked with the transmission of pathogenic fungi, contributing to spoilage and the production of mycotoxins. Rodents, including *Rattus rattus* (black rat) and *Mus musculus* (house mouse), cause both direct consumption losses and indirect damage through gnawing, contamination with droppings, and spreading of diseases such as leptospirosis and salmonellosis (Ganjeer *et.al.,* 2021). It is estimated that rodents consume and contaminate enough food annually to feed over 200 million people. Effective rodent-proof storage structures and constant monitoring are essential components of integrated pest control strategies.

***C. Pest biology and ecology relevant to storage environments***

Stored product pests have evolved unique adaptations to the storage environment. These include rapid reproductive rates, tolerance to low-moisture content, and the ability to hide in crevices and residual grain dust. Most insect pests thrive in warm and humid conditions, with optimum development occurring between 25–35°C and relative humidity above 65%.The lifecycle duration of pests varies widely. For example, *S. oryzae* completes development in 26–32 days at 30°C and 70% RH, while *T. castaneum* may take 30–50 days under similar conditions. Pest survival is also influenced by grain type, moisture content, and the presence of microbial communities.The spatial distribution of pests within storage structures is often aggregated, with higher populations found near heat-generating sources and poorly ventilated areas (Jones *et.al.,* 2006). This knowledge is critical for the design of targeted pest detection and management systems.

***D. Pest resistance development to traditional insecticides***

Increased reliance on chemical control has led to the evolution of resistance among many stored product pest species. Resistance to phosphine, one of the most widely used fumigants, has been documented in populations of *R. dominica*, *T. castaneum*, and *S. oryzae* across multiple continents. The mechanism of resistance to phosphine involves both metabolic detoxification and altered respiratory pathways, with high heritability and persistence across generations. Populations of *T. castaneum* have also developed resistance to pyrethroids, carbamates, and organophosphates, reducing the efficacy of surface sprays and grain protectants. Long-term use of insecticides without rotation or monitoring accelerates resistance buildup and leads to control failures, product loss, and greater reliance on high-risk chemicals (Jutsum *et.al.,* 1998). Implementing resistance management strategies, such as insecticide rotation and integration of non-chemical control methods, is critical for long-term pest suppression.

**IV. Conventional Control Methods and Their Drawbacks**

***A. Chemical fumigants (e.g., phosphine, methyl bromide)***

Chemical fumigants have long served as a primary method for controlling insect pests in stored commodities due to their deep penetration, broad-spectrum activity, and cost-effectiveness (Stejskal *et.al.,* 2021). Among these, **phosphine (PH₃)** and **methyl bromide (CH₃Br)** have been the most widely used.**Phosphine**, generated from aluminum or magnesium phosphide, is extensively applied in stored grain systems. It is effective against all life stages of insects, from eggs to adults. At a concentration of 500–600 ppm over a 7-day exposure at 25–30°C, phosphine achieves near-complete mortality of pests like *Tribolium castaneum*, *Sitophilus oryzae*, and *Rhyzopertha dominica*. Despite its advantages, repeated use has led to widespread resistance. Studies have reported resistant populations of *R. dominica* and *T. castaneum* in multiple countries, reducing fumigant effectiveness. **Methyl bromide** was once considered a universal fumigant due to its rapid action and ability to penetrate deeply into bulk commodities and packaging materials. It was particularly favored for quarantine and pre-shipment (QPS) applications. Despite its effectiveness, methyl bromide is classified as an ozone-depleting substance under the Montreal Protocol. Its global phase-out began in 2005, with few exemptions remaining for critical uses. Toxicological concerns also surround its use, including central nervous system effects and potential carcinogenicity (Wogan *et.al.,* 2004).

***B. Residual insecticides***

Residual insecticides are commonly used for treating storage structures, bag surfaces, and equipment to provide long-term protection. The major classes include organophosphates (e.g., malathion, pirimiphos-methyl), pyrethroids (e.g., deltamethrin, cypermethrin), and insect growth regulators (IGRs) such as methoprene and hydroprene. **Organophosphates**, such as malathion, were once widely applied due to their low cost and broad-spectrum action. Over time, their repeated use has led to resistance in key pest species. For example, *T. castaneum* populations in several grain storage facilities have developed significant resistance to malathion, rendering it largely ineffective. **Pyrethroids**, known for their knockdown effect and relatively low mammalian toxicity, are often used for structural treatment (Gajendiran *et.al.,* 2018). Deltamethrin has shown good efficacy on concrete and metal surfaces; however, its performance diminishes on dusty or porous surfaces. Resistance has also emerged in certain populations, particularly when used without rotation. **Insect growth regulators** interfere with insect molting and development. Methoprene, for example, has shown promising control over *T. castaneum* and *P. interpunctella*, especially when used in combination with other insecticides. Although resistance development to IGRs is slower, their efficacy is often limited to immature stages, necessitating combination with adulticides (Hafez *et.al.,* 2021).

***C. Risks: environmental contamination, human health, pest resistance***

The over-reliance on synthetic insecticides and fumigants has resulted in several critical risks:

***Environmental contamination***

Persistent chemicals such as organochlorines (e.g., lindane, DDT), although now banned in many countries, have left long-lasting residues in soil and water (Ali *et.al.,* 2021). Current insecticides, while less persistent, still contribute to contamination through volatilization, leaching, and runoff. Surface treatments can also lead to accumulation of residues in grain dust, potentially impacting non-target organisms.

***Human health hazards***

Improper application of fumigants or insecticides can lead to acute and chronic health effects. Exposure to phosphine gas, even at low concentrations (above 0.3 ppm), may cause respiratory distress, dizziness, and nausea. Workers handling fumigants without adequate protection are at high risk of poisoning. Malathion and other organophosphates are associated with neurotoxicity due to inhibition of acetylcholinesterase, while methyl bromide has been linked to reproductive toxicity and CNS depression (Rohlman *et.al.,* 2022).

***Resistance development***

Repeated exposure to the same active ingredients, without rotation or adequate pest monitoring, has led to accelerated resistance development. Resistance to phosphine is now widespread and includes high-level resistance (more than 1,000-fold) in certain *R. dominica* populations. Resistance not only undermines efficacy but also increases the cost and complexity of pest management strategies (Jutsum *et.al.,* 1998).

***D. Regulatory restrictions and phase-outs of certain chemicals***

Global and regional regulatory bodies have enacted strict controls on the use of hazardous pesticides and fumigants:

* **Methyl bromide**: Banned or severely restricted in over 160 countries under the Montreal Protocol due to its ozone-depleting potential. Exemptions are granted only for quarantine and certain critical uses.
* **Organochlorines**: Compounds like DDT, aldrin, and lindane are listed under the Stockholm Convention on Persistent Organic Pollutants and have been banned due to their persistence and bioaccumulation (Matthies *et.al.,* 2016).
* **Phosphine**: While not banned, regulatory agencies such as the US EPA and EU Commission have tightened guidelines on its use due to increasing resistance and concerns about occupational exposure. Recent mandates include the need for certified applicators, restricted entry intervals, and gas monitoring during fumigation.
* **Organophosphates**: Substances like chlorpyrifos and diazinon are now under review or banned in many regions due to their neurotoxic effects and risks to pollinators and aquatic life (Zaller *et.al.,* 2020).

**V. Eco-Friendly Technologies in Pest Management**

***A. Botanical Pesticides and Plant-Based Products***

Botanical pesticides represent a sustainable and environmentally benign alternative to synthetic insecticides. Derived from plants, these substances possess insecticidal, antifeedant, or repellent properties. Many contain complex mixtures of secondary metabolites such as terpenoids, alkaloids, phenolics, and flavonoids.

***1. Essential oils (e.g., neem, clove, eucalyptus)***

Essential oils extracted from aromatic plants exhibit a broad spectrum of insecticidal and repellent activities. **Neem oil** (*Azadirachta indica*) contains azadirachtin, a well-documented growth inhibitor and antifeedant. At 0.5–2% concentrations, neem oil has shown mortality rates exceeding 85% against *Sitophilus oryzae* and *Callosobruchus chinensis* within 7 days. **Clove oil** (*Syzygium aromaticum*), rich in eugenol, demonstrates contact and fumigant toxicity. A study reported 100% mortality of *T. castaneum* adults at 10 μL/L air concentration within 24 hours. **Eucalyptus oil** has also exhibited fumigant properties; it induces neurotoxicity in insects by disrupting acetylcholinesterase activity (Yeom *et.al.,* 2013).

***2. Plant powders and extracts***

Crushed plant materials and aqueous/alcoholic extracts serve as traditional pest control agents. **Garlic powder** and **chili extracts** have been tested against stored grain pests with moderate to high repellency and mortality. **Peppermint, basil, and rosemary powders** also show repellent actions, likely due to monoterpenes and phenolic compounds (Moore *et.al.,* 2006). Plant powders are more stable during storage than essential oils, although their efficacy tends to be slower. Their use as grain protectants has shown promising results when applied at rates of 2–5 g/kg grain.

***3. Mode of action and efficacy***

Plant-based products interfere with insect behavior, physiology, and reproduction through:

* **Neurotoxicity** – inhibition of acetylcholinesterase, as seen with eugenol and linalool.
* **Growth inhibition** – azadirachtin disrupts molting by interfering with ecdysteroid hormones.
* **Respiratory blockage** – oils with high vapor pressure create suffocating atmospheres for insects.
* **Repellency and oviposition deterrence** – monoterpenes such as citronellal repel adult insects from laying eggs (Reis *et.al.,* 2016).

***B. Biological Control Agents***

Biological control involves the use of natural enemies or microbial agents to suppress pest populations. These include entomopathogenic fungi, bacteria, viruses, parasitoids, and predators.

***1. Entomopathogenic fungi, bacteria, and viruses***

Fungal agents such as *Beauveria bassiana and Metarhizium anisopliae* infect insects via cuticle penetration, leading to dehydration and death (Mannino *et.al.,* 2019). Laboratory trials have shown >90% mortality in *T. castaneum* and *R. dominica* at spore concentrations of 1 × 10⁸ conidia/m. *Bacillus thuringiensis* (Bt), a spore-forming bacterium, is effective against lepidopteran larvae such as *Plodia interpunctella* through the production of δ-endotoxins that disrupt gut epithelial cells. Entomopathogenic **viruses**, particularly nucleo polyhedron viruses (NPVs), have shown potential against moth larvae. They are host-specific and biodegradable, with minimal environmental impact.

***2. Parasitoids and predators***

Hymenopteran parasitoids such as *Anisopteromaluscalandrae* and *Theocolax elegans* parasitize larvae or pupae of beetle pests like *S. oryzae* and *R. dominica*, reducing emergence by over 60% under lab conditions (Toews *et.al.,* 2001). Predators like *Xylocoris flavipes*, a generalist bug, feed on all developmental stages of stored product insects. Biocontrol using natural enemies requires careful environmental control and may perform best under hermetic or semi-controlled storage conditions.

***3. Integration into IPM frameworks***

Biological control agents are most effective when used as part of **Integrated Pest Management (IPM)** programs. Combining entomopathogens with monitoring tools, botanicals, and sanitation practices enhances efficacy and sustainability. For example, B. bassiana can be applied with diatomaceous earth to improve residual action. Challenges include humidity requirements for fungal agents and slower kill rates compared to chemical options (Juroszek *et.al.,* 2022). Despite this, biological tools provide long-term suppression with minimal ecological disruption.

***C. Physical and Mechanical Control Methods***

Non-chemical control methods play an essential role in stored product protection, especially in low-resource and organic systems. These methods target pest survival through atmospheric, thermal, or abrasive means.

***1. Modified atmospheres (e.g., low oxygen, CO₂ enrichment)***

Modifying atmospheric composition through **low oxygen (<2%)** or **high carbon dioxide (>60%)** conditions induces anoxia, leading to insect mortality by disrupting cellular respiration (Mitcham *et.al.,* 2006). Hermetic storage systems, such as PICS (Purdue Improved Crop Storage) bags, utilize this principle and have shown high efficacy against weevils and bruchids without chemical additives. Controlled atmospheres are scalable and suitable for both small-scale and bulk storage, though they require airtight structures and may have longer treatment durations (5–15 days).

***2. Temperature treatments (heat and cold treatments)***

Thermal disinfestation exploits insect sensitivity to extreme temperatures. Exposure to **temperatures above 50°C for 5–10 minutes** or **below –10°C for 7–14 days** causes mortality in most pest species. Heat treatments are commonly used for flour mills and warehouses, while cold storage is suitable for high-value packaged foods.

***3. Inert dusts and diatomaceous earth***

Inert materials such as **diatomaceous earth (DE)** and kaolin act by abrading the insect cuticle, leading to desiccation (Ebeling *et.al.,* 1959). DE application at 0.5–1.0% w/w has shown 80–100% mortality of *S. oryzae* and *T. castaneum* under dry conditions. Silica gel formulations further enhance efficacy by increasing surface area and absorbency.

***D. Biodegradable Packaging and Coatings***

Recent innovations in food-grade packaging aim to integrate pest control properties while maintaining environmental sustainability.

***1. Natural polymers with pest-repellent properties***

Biodegradable films made from **chitosan, starch, gelatin, and cellulose** are being tested for use as protective coatings (Ahmed *et.al.,* 2016). Chitosan, derived from crustacean shells, exhibits antimicrobial and insect-repellent activity, making it suitable for coating grain or seed packaging.

***2. Integration of botanicals into packaging materials***

Incorporating essential oils and plant extracts into polymer matrices enhances their pest-repellent and antimicrobial functions. For instance, chitosan films loaded with **clove or cinnamon oil** inhibit fungal growth and repel *T. castaneum* for up to 60 days. Nano-encapsulation of these bioactives improves stability and controlled release.

**VI. Recent Advances in Pest Monitoring and Detection Tools**

***A. Pheromone-Based Monitoring Systems***

The use of pheromone-based systems has transformed pest monitoring in stored product environments by offering a targeted, non-toxic, and efficient means of detecting early infestations (Murugesan *et.al.,* 2024). These systems exploit chemical signals that insects naturally emit to communicate, particularly for mating and aggregation. Two major categories of pheromones are used for monitoring purposes: aggregation pheromones and sex attractants. Aggregation pheromones attract both sexes and are primarily used for species such as *Tribolium castaneum* and *Rhyzopertha dominica*. These compounds have been synthesized and standardized, with kairomonal synergy enhancing their field efficacy in detecting hidden infestations. On the other hand, sex pheromones are typically female-emitted volatiles that attract males, often applied for monitoring moths like *Plodia interpunctella* and *Ephestia cautella*. The use of synthetic analogs allows for consistent performance across diverse storage conditions and seasons. Trap designs play a crucial role in the success of pheromone-based monitoring systems. Dome traps, pitfall traps, and sticky traps have been optimized for different pest behaviors and locations (Sahayaraj *et.al.,* 2023). Pitfall traps, baited with aggregation pheromones and food oil, effectively monitor walking beetles on grain surfaces and warehouse floors. Adhesive traps placed vertically near light sources or food shelves are more suitable for flying moths and beetles. Placement strategy involves spatial mapping of the facility, with traps positioned in high-risk zones such as corners, loading docks, and warm spots to detect emerging populations before visible signs of infestation occur. Pheromone traps not only help in early warning but also assist in evaluating the success of control interventions and in making decisions for threshold-based management.

***B. Electronic and Smart Traps***

The integration of electronics into pest monitoring has created intelligent systems capable of real-time data collection and analysis (Potamitis *et.al.,* 2017). Automated pest detection using optical or motion sensors has enabled continuous surveillance of storage environments without the need for manual inspection. These sensors detect and count insect entries into a trap by recording interruptions in light beams or changes in electrical resistance. Such technologies have been developed for pests like *T. castaneum* and *S. oryzae*, demonstrating detection accuracy rates above 90% under laboratory and semi-field conditions. Modern smart traps are often embedded with Internet of Things (IoT) technology, allowing for remote pest surveillance. These traps transmit real-time data on pest captures to cloud-based platforms via wireless networks. The data collected can be visualized using user-friendly dashboards, enabling facility managers to observe temporal and spatial patterns of pest activity (Kumari *et.al.,* 2024). Alerts can be generated when captures exceed predefined thresholds, prompting timely interventions. This connectivity significantly reduces labor costs, improves decision-making speed, and enhances precision in pest control strategies. Data analytics plays a vital role in deriving actionable insights from electronic monitoring. Advanced algorithms and machine learning models process captured data to identify trends, predict pest outbreaks, and optimize control schedules. Geographic Information System (GIS)-based tools help visualize pest hotspots within a facility, enabling localized treatment rather than blanket application of pesticides (Huang *et.al.,* 2008). These systems are increasingly being adopted in high-value storage systems such as grain silos, food processing units, and seed storage facilities, where early detection and contamination avoidance are critical.

***C. Spectroscopy and Imaging Techniques***

Optical methods such as spectroscopy and imaging have introduced non-destructive and high-throughput solutions for pest detection. Near-Infrared Spectroscopy (NIRS) is an analytical technique that detects differences in the absorbance of light at specific wavelengths to distinguish between infested and uninfested grains. NIRS has been successfully applied to identify *S. oryzae* larvae inside wheat kernels with over 95% accuracy, based on spectral shifts caused by internal damage and moisture gradients (Zhang *et.al.,* 2021). This technique is rapid, chemical-free, and can be integrated with conveyor belts for inline inspection in grain processing facilities. Hyperspectral imaging extends the capabilities of NIRS by combining spatial and spectral information to detect subtle variations in sample composition. It has been applied to detect insect damage in rice, maize, and beans by analyzing reflectance patterns at hundreds of wavelengths. Studies have reported over 90% classification accuracy in distinguishing infested kernels using machine learning algorithms trained on hyperspectral data. Hyperspectral systems are particularly useful for detecting early-stage infestations, fungal growth, or quality deterioration that is not visible to the naked eye. Though current systems are expensive, advances in sensor miniaturization and processing software are expected to lower the barrier to adoption.

***D. Molecular and Genetic Tools***

Recent advances in molecular diagnostics have offered highly accurate tools for species identification, resistance monitoring, and detection of cryptic infestations (Spadaro *et.al.,* 2020). DNA barcoding uses short genetic sequences, typically from the mitochondrial COI gene, to differentiate between pest species, even at the larval or egg stage. This is especially valuable in identifying morphologically similar species such as *Sitophilus oryzae*, *S. zeamais*, and *S. granarius*, which vary in their ecological preferences and resistance profiles. Molecular assays have also been developed to detect genetic mutations associated with pesticide resistance. For example, specific point mutations in the cytochrome oxidase gene of *T. castaneum* have been linked with phosphine resistance, and these can be identified through PCR-based techniques within a few hours. Monitoring resistance genes helps adjust pest management programs proactively before widespread control failures occur (Knight *et.al.,* 2021). Emerging research into CRISPR/Cas-based diagnostics holds promise for field-deployable and ultra-sensitive detection. CRISPR-based biosensors can identify specific nucleic acid sequences of target pests or resistance markers by producing a fluorescent signal upon detection. Such systems, still in development stages, could provide on-site, paper-strip-based testing methods requiring minimal technical expertise and infrastructure. Their application could revolutionize stored product protection by enabling real-time, genetic-level diagnostics in remote or decentralized storage sites.

**VII. Integration of Eco-Friendly Approaches into IPM Programs**

***A. Principles of Integrated Pest Management (IPM)***

Integrated Pest Management (IPM) is a holistic approach to pest control that combines multiple methods and tools to manage pest populations at levels below those causing economic harm (Barzman *et.al.,* 2015). Its core principle is the integration of biological, physical, cultural, and chemical control tactics based on pest ecology, economic thresholds, and environmental impact. IPM aims to minimize risks to human health and the environment while maintaining pest populations within acceptable limits.

***B. Case studies of successful IPM in storage systems***

Several successful implementations of IPM strategies in storage systems demonstrate the efficacy of combining eco-friendly technologies with structured management. A notable example is the use of hermetic storage bags combined with sanitation and botanical treatments for cowpea storage in West Africa (Bakoye *et.al.,* 2020). Research reported near-complete control of *Callosobruchus maculatus* over a 6-month period using Purdue Improved Crop Storage (PICS) bags without the application of chemical insecticides. Another case involved the application of diatomaceous earth (DE) in combination with essential oils for stored wheat protection against *Sitophilus oryzae* and *Tribolium castaneum*. Laboratory and small-scale trials showed that DE at 1.0% (w/w) along with 0.5% clove oil reduced adult emergence by over 90% after 28 days of storage. These trials demonstrated that combining physical and botanical methods can enhance efficacy and reduce required application rates. In commercial settings, IPM programs utilizing pheromone traps for *Plodia interpunctella* monitoring, combined with sanitation and insect growth regulators (IGRs), have resulted in significant reductions in moth captures and product damage. For instance, 65% reduction in trap counts in a flour mill after implementation of an IPM protocol based on frequent cleaning, targeted IGR fogging, and pheromone-based decision support (Phillips *et.al.,* 2010).

***C. Synergistic effects of combining monitoring and eco-friendly methods***

The success of IPM lies in its capacity to integrate multiple compatible tools that enhance each other's performance. Combining monitoring systems with eco-friendly interventions leads to more timely and precise actions, improving pest control outcomes and reducing unnecessary treatments. Pheromone-based traps, when used as decision-support tools, help to optimize the timing of biological applications such as *Beauveria bassiana* or diatomaceous earth, ensuring that these agents are deployed during peak pest activity (Gerken *et.al.,* 2022). Thermal treatments, when guided by hotspot detection from electronic monitoring systems, can be localized to specific zones, reducing energy use and exposure of non-infested areas. For example, targeted heat disinfestation of grain bins where sensor data revealed increased *Rhyzopertha dominica* activity was shown to reduce infestation rates by over 80% while using 40% less energy compared to whole-bin treatments. Synergies are also evident in combining entomopathogenic fungi with inert dusts. Studies have reported enhanced efficacy of *Beauveria bassiana* when applied with silica aerogels, as the dust facilitates spore adhesion and desiccation. Similarly, botanical insecticides with repellence properties, such as eugenol and citronellal, can be incorporated into packaging materials to extend protection and prevent reinfestation during transit (Navarro *et.al.,* 2007).

***D. Challenges and limitations in practical adoption***

Despite the proven efficacy of eco-friendly and integrated methods, their large-scale adoption faces several challenges. One of the primary barriers is the lack of user awareness and training on the proper application and integration of non-chemical methods. Many storage facility operators and smallholder farmers rely on traditional practices or overuse chemical insecticides due to perceived simplicity and immediate results. Cost and availability of some eco-friendly technologies can also hinder implementation. For example, high-purity essential oils and formulated biopesticides may not be readily accessible in remote regions, or may be priced higher than conventional pesticides. Additionally, certain methods such as biological control require specific environmental conditions (e.g., humidity for fungal pathogens), which may not always be met in storage environments. Another limitation involves the speed of action. Unlike synthetic chemicals, many eco-friendly solutions have slower knockdown effects, which may be viewed as a disadvantage in situations requiring immediate pest suppression (Vurro *et.al.,* 2019). For instance, entomopathogenic fungi typically require 5–7 days to induce mortality in target pests, which might be insufficient during high-infestation scenarios. Regulatory and policy frameworks may also lag in supporting alternatives. Limited registration of botanical and microbial agents in national pest control programs can delay their commercial use. Consistency and standardization in efficacy data for these agents are often lacking, making it difficult to compare across studies and applications. Nevertheless, increasing concerns over pesticide residues, environmental degradation, and resistance development are pushing regulatory bodies and industry stakeholders to invest in sustainable pest management models. Integration of eco-friendly tools into IPM frameworks represents a resilient, long-term strategy for stored product protection.

**VIII. Regulatory, Economic, and Social Considerations**

The transition to eco-friendly pest management technologies in stored product protection has been supported by national and international regulatory frameworks that emphasize sustainability, food safety, and environmental health (Fortunati *et.al.,* 2019). The International Code of Conduct on Pesticide Management developed by FAO and WHO promotes reduced reliance on hazardous chemicals and encourages the adoption of biologicals, botanicals, and integrated pest management (IPM) strategies. Regulatory agencies such as the European Food Safety Authority (EFSA) and the US Environmental Protection Agency (EPA) have increasingly limited the use of broad-spectrum pesticides while providing fast-track registration procedures for low-risk biopesticides. From an economic perspective, several studies have demonstrated that although the initial costs of eco-friendly interventions may be higher than conventional methods, the long-term return on investment can be favorable due to reduced chemical inputs, minimized resistance buildup, and access to premium markets. For example, adoption of hermetic storage technology in Sub-Saharan Africa has shown benefit-cost ratios ranging from 2.3 to 4.1 over a 12-month storage period (Ndaka *et.al.,* 2012). Adoption, however, remains influenced by levels of awareness, accessibility of inputs, and farmer training. Surveys conducted across Southeast Asia and parts of Africa indicate that only 15–30% of smallholder farmers have regular access to training on non-chemical storage practices, while extension services often lack the capacity to deliver localized support. Public perception also plays a pivotal role, as rising concerns about food safety and pesticide residues have driven increased consumer demand for residue-free and organically stored commodities (Chikte *et.al.,* 2024). A study showed that 65% of European consumers expressed a strong preference for food with minimal pesticide use, directly influencing procurement policies of grain buyers and retailers. Market trends reflect a growing shift toward sustainable certification schemes, such as organic or IPM-certified storage, which can serve as economic incentives for both producers and supply chain actors to adopt eco-friendly pest management approaches.

**IX. Challenges and Future**

Despite the progress in developing eco-friendly and non-chemical solutions for stored product pest management, several critical challenges continue to limit their full-scale implementation (Tedesco *et.al.,* 2023). Research gaps persist in understanding the long-term field efficacy, residual activity, and sub-lethal effects of many botanical and biological agents under diverse storage conditions. For example, entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* exhibit promising laboratory results, but their field performance is often inconsistent due to variable humidity, grain moisture, and temperature profiles. Moreover, the absence of internationally standardized testing protocols makes it difficult to compare efficacy across different formulations and geographies. There is a pressing need for coordinated efforts in validating eco-friendly products through multi-location field trials and establishing globally accepted benchmarks for performance and safety. Another major barrier lies in the scalability and affordability of these solutions for small and medium-scale storage operators. While hermetic storage systems, biopolymer packaging, and sensor-based monitoring tools have shown success at pilot levels, cost constraints and supply chain limitations impede their widespread adoption. Future development must focus on designing modular, user-friendly, and cost-efficient technologies that can be integrated seamlessly into existing storage infrastructures (Coppola *et.al.,* 2020). Integration with digital agriculture tools offers a promising direction. Precision pest management platforms that combine real-time sensor data, machine learning algorithms, and geospatial mapping can enable site-specific interventions and reduce resource wastage. Systems such as automated trap monitoring, remote-controlled fumigation units, and cloud-based pest prediction models have already shown potential in high-value grain storage operations. Effective implementation of these innovations, however, requires active collaboration between researchers, policymakers, and industry stakeholders. Public-private partnerships and knowledge exchange platforms can accelerate the commercialization and adoption of validated technologies. Policy support through subsidies, extension training, and inclusive regulation of green products will be critical in shaping the next generation of sustainable stored product protection strategies. Without a coordinated global framework, the transition to safer, resilient, and scalable pest management systems will remain fragmented and slow, despite increasing urgency from both ecological and market perspectives (Heeb *et.al.,* 2019).

**X. Conclusion**

The advancement of eco-friendly technologies and precision monitoring tools presents a sustainable path forward in stored product pest management. Botanical pesticides, biological agents, and physical control methods offer effective alternatives to chemical fumigants, reducing environmental impact and health risks. Integration of these tools within IPM frameworks, supported by digital surveillance and data-driven decision-making, enhances pest control efficacy while minimizing resistance development. Case studies demonstrate that such approaches are both economically viable and environmentally responsible. Regulatory support, market demand for residue-free grains, and increased farmer awareness are driving the shift toward greener solutions. Challenges remain in terms of scalability, standardization, and field-level validation, but ongoing research and multi-stakeholder collaboration provide a strong foundation for future innovation. Emphasizing eco-safe strategies is essential for securing global food systems and ensuring long-term grain storage sustainability.

**COMPETING INTERESTS DISCLAIMER:**

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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