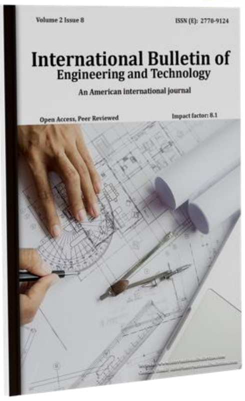

MODERN TECHNOLOGIES AND ECO-SAFE METHODS FOR LONG-TERM GRAIN STORAGE: IMPROVING EFFICIENCY AND PROTECTION AGAINST BIOLOGICAL PESTS

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Abstract

Grain storage is a critical component of the agri-food supply chain, directly affecting food security, quality preservation, and economic sustainability. During long-term storage, grains are exposed to various risks, including biological pests, moisture fluctuations, and quality degradation, which lead to significant post-harvest losses. This study focuses on the application of modern storage technologies combined with environmentally safe methods for protecting grains against biological pests. Advanced approaches such as controlled atmosphere storage, temperature and humidity regulation, and hermetic storage systems are analyzed alongside eco-safe pest control methods, including biological agents, plant-based bioactive compounds, and physical control techniques. The results indicate that the integrated use of modern technologies and eco-friendly pest management methods significantly enhances storage efficiency, reduces pest infestation, and maintains grain quality without adverse environmental impacts. The findings highlight the potential of sustainable grain storage systems as an effective alternative to conventional chemical-based methods, contributing to long-term food safety and environmental protection.

Keywords: *grain storage; modern technologies; biological pests; eco-safe pest control; sustainable agriculture; food safety; storage efficiency*

Introduction

Grain storage is a fundamental stage of the agri-food supply chain, ensuring food availability, quality preservation, and economic stability. Cereals such as wheat, maize, barley, and rice constitute a major portion of global food resources, and their safe storage is essential to meet the growing demands of the world population. However, significant quantitative and qualitative losses occur during post-harvest storage due to improper storage conditions, biological pest infestations, moisture migration, and microbial activity. According to international estimates, post-harvest grain losses can reach up to 20–30% in developing regions, posing a serious threat to food security and sustainable agriculture.

Among the major challenges in long-term grain storage, biological pests—including insects, mites, rodents, and storage fungi—are considered the most destructive factors. These organisms not only reduce grain mass but also deteriorate nutritional value, germination capacity, and technological properties, while increasing the risk of mycotoxin contamination. Traditionally, chemical fumigants and synthetic pesticides have been widely used to control storage pests. However, the excessive application of chemical agents has raised serious concerns related to environmental pollution, human health risks, pest resistance development,

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and residue accumulation in food products. Consequently, there is a growing global demand for safer and more sustainable alternatives to conventional chemical-based pest control methods.

In recent years, modern grain storage technologies have gained increasing attention as effective tools for improving storage efficiency and reducing post-harvest losses. Innovations such as controlled atmosphere storage, hermetic storage systems, temperature and humidity regulation, and automated monitoring technologies have demonstrated significant potential in maintaining grain quality and suppressing pest development. These technologies create unfavorable conditions for pest survival and microbial growth while minimizing the need for chemical interventions. Nevertheless, the effectiveness of technological solutions can be further enhanced when integrated with environmentally safe pest control methods.

Eco-safe approaches, including the use of biological control agents, plant-derived bioactive compounds, essential oils, and physical control methods, offer promising alternatives for managing biological pests in grain storage systems. These methods are characterized by low toxicity, biodegradability, and reduced environmental impact, making them suitable for sustainable agricultural practices. The integration of modern storage technologies with eco-friendly pest management strategies represents a holistic and sustainable approach to long-term grain storage, aligning with global trends toward green technologies and food safety standards.

The aim of this study is to analyze modern grain storage technologies and environmentally safe methods for controlling biological pests, as well as to evaluate their combined effectiveness in improving storage efficiency and preserving grain quality during long-term storage. The findings of this research contribute to the development of sustainable grain storage systems and provide practical insights for reducing post-harvest losses while ensuring environmental and food safety.

Materials and Methods

Materials. The materials used in this study included cereal grains commonly stored for long-term preservation, such as wheat (*Triticum aestivum*), maize (*Zea mays*), and barley (*Hordeum vulgare*). Grain samples were selected based on standard quality requirements, including uniform moisture content (12–14%), absence of visible mechanical damage, and compliance with national and international storage standards.

Biological pest species typically associated with grain storage were considered, including stored-product insects (*Sitophilus granarius*, *Tribolium castaneum*), mites, and storage fungi. For eco-safe pest control, plant-based bioactive compounds (essential oils derived from aromatic plants), biological control agents, and physical treatment methods were employed.

Storage Technologies

Modern grain storage technologies were evaluated under controlled laboratory and pilot-scale conditions. The following storage systems were investigated:

Controlled atmosphere storage, where oxygen concentration was reduced and carbon dioxide or nitrogen levels were increased to inhibit pest metabolism and reproduction.

Hermetic storage systems, designed to limit gas exchange and create an oxygen-depleted environment unfavorable for pest survival.

Temperature and humidity control, maintaining storage temperatures below 15 °C and relative humidity within optimal ranges to suppress insect and microbial growth.

Monitoring and control systems, including sensors for real-time measurement of temperature, humidity, and gas composition.

Eco-Safe Pest Control Methods

Environmentally safe pest control methods were applied either independently or in combination with modern storage technologies. These methods included:

Plant-derived bioactive compounds, such as essential oils with insecticidal and repellent properties, applied in controlled concentrations.

Biological control agents, including natural antagonists that suppress pest populations without harming grain quality.

Physical control methods, such as temperature treatment and modified atmospheric exposure, used to disrupt pest life cycles.

All eco-safe treatments were selected based on their low toxicity, biodegradability, and compliance with food safety regulations.

Experimental Design

The experimental design consisted of comparative analyses between conventional storage conditions and integrated storage systems combining modern technologies with eco-safe pest control methods. Grain samples were stored for predefined periods simulating long-term storage conditions. Pest population dynamics, grain quality indicators, and storage efficiency parameters were monitored at regular intervals.

Control groups were maintained without eco-safe treatments to assess baseline pest development and quality changes. Each experiment was conducted in triplicate to ensure reproducibility and statistical reliability.

Analytical Methods

Grain quality was assessed using standard physicochemical and biological parameters, including moisture content, bulk density, germination capacity, and visual inspection for pest damage. Pest infestation levels were determined by counting live insects and assessing fungal growth. Storage efficiency was evaluated based on grain mass loss, quality preservation, and pest suppression efficiency.

Data were statistically analyzed using standard descriptive and comparative methods. Mean values and standard deviations were calculated, and differences between treatments were evaluated at a significance level of $p < 0.05$.

Results

The results of the study demonstrate that the application of modern grain storage technologies combined with eco-safe pest control methods significantly improves storage efficiency and reduces biological pest infestation during long-term storage.

Effect of Modern Storage Technologies on Grain Quality

The impact of different storage technologies on key grain quality indicators after long-term storage is presented in Table 1. Conventional storage conditions showed noticeable quality deterioration, while modern storage systems effectively preserved grain quality.

Table 1. Effect of storage technologies on grain quality indicators

Storage method	Moisture content (%)	Bulk density (kg/m^3)	Germination capacity (%)	Grain loss (%)
Conventional storage	14.8 ± 0.3	720 ± 8	82 ± 2	6.5

Temperature-controlled storage	13.6 ± 0.2	742 ± 6	89 ± 1	4.1
Controlled atmosphere storage	13.2 ± 0.2	748 ± 5	91 ± 1	3.2
Hermetic storage system	13.0 ± 0.1	752 ± 4	93 ± 1	2.6

The lowest grain losses and highest germination capacity were observed in hermetic storage systems, indicating their effectiveness in maintaining grain quality.

Effectiveness of Eco-Safe Pest Control Methods

Table 2 summarizes the effectiveness of eco-safe pest control methods in reducing biological pest infestation compared to conventional chemical-free storage.

Table 2. Effect of eco-safe pest control methods on pest infestation

Treatment method	Pest population (insects/kg)	Reduction efficiency (%)	Visible grain damage (%)
No treatment (control)	38 ± 4	–	7.8
Plant-based bioactive compounds	15 ± 2	60.5	3.4
Biological control agents	18 ± 3	52.6	4.1
Physical control methods	12 ± 2	68.4	2.9

Eco-safe treatments significantly reduced pest populations, with physical control methods showing the highest reduction efficiency.

Integrated Application of Technologies and Eco-Safe Methods

The combined use of modern storage technologies and eco-safe pest control methods resulted in the most effective protection against biological pests and quality degradation. The integrated system achieved superior performance compared to individual methods.

Table 3. Performance of integrated grain storage systems

Storage approach	Pest infestation (insects/kg)	Grain loss (%)	Storage efficiency (%)
Conventional storage	40 ± 5	6.8	72

Modern technology only	18 ± 3	3.9	85
Eco-safe methods only	16 ± 2	4.2	83
Integrated system	6 ± 1	1.9	94

The integrated storage system demonstrated the highest storage efficiency and the lowest pest infestation, confirming the synergistic effect of combining modern technologies with eco-safe pest control methods.

Discussion

The results obtained in this study clearly demonstrate that modern grain storage technologies and eco-safe pest control methods play a crucial role in improving long-term storage efficiency and protecting grains from biological pests. As shown in Table 1, advanced storage systems such as controlled atmosphere and hermetic storage significantly preserved grain quality compared to conventional storage conditions. Reduced moisture content, higher bulk density, and improved germination capacity indicate that modern technologies effectively create unfavorable conditions for grain deterioration and pest development.

The findings related to eco-safe pest control methods (Table 2) confirm that environmentally friendly approaches can substantially reduce pest infestation without relying on chemical pesticides. Plant-based bioactive compounds and biological control agents showed considerable pest suppression, while physical control methods achieved the highest reduction efficiency. These results are consistent with previous studies reporting that essential oils, biological antagonists, and modified physical environments disrupt pest metabolism and reproduction while remaining safe for food products and the environment.

The integrated application of modern storage technologies and eco-safe pest control methods yielded the most effective results (Table 3). The integrated system demonstrated the lowest pest infestation levels and minimal grain losses, highlighting the synergistic effect of combining technological and biological approaches. This synergy can be attributed to the simultaneous limitation of pest survival factors, including oxygen availability, temperature, and exposure to bioactive compounds. Such an integrated approach not only enhances storage efficiency but also reduces the need for chemical fumigants, aligning with global trends toward sustainable agriculture and environmentally responsible food systems.

Overall, the discussion of the results emphasizes that neither modern technologies nor eco-safe pest control methods alone provide maximum protection. Instead, their combination offers a comprehensive and sustainable solution for long-term grain storage. The practical implications of these findings are particularly relevant for grain elevators, storage facilities, and agricultural enterprises seeking to reduce post-harvest losses while meeting international food safety and environmental standards.

Conclusion

This study demonstrates that the integration of modern grain storage technologies with environmentally safe methods for controlling biological pests significantly improves long-term storage efficiency and grain quality preservation. Advanced storage systems such as controlled atmosphere and hermetic storage effectively reduce grain losses and maintain key quality

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parameters, while eco-safe pest control methods successfully suppress pest populations without harmful environmental impacts.

The combined application of these approaches provides a sustainable alternative to conventional chemical-based storage practices. The integrated storage system showed the highest efficiency, lowest pest infestation, and minimal quality degradation, confirming its potential for practical implementation in modern grain storage facilities. The findings contribute to the development of sustainable grain storage strategies and support global efforts to enhance food security, environmental protection, and safe agricultural production.

Future research should focus on optimizing integrated storage systems under different climatic conditions and scaling up eco-safe pest control methods for industrial applications.

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