Original Research

EAST AFRICAN JOURNAL OF PASTORALISM
Volume 5 Issue 2

Eco-Friendly Viable Options for The Management of Stored Pearl Millet *Pennisetum Glaucum (L.)* Against Storage Insect Pests

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ABSTRACT

The management of storage insect pests in pearl millet *(Pennisetum glaucum L.)*, a vital cereal crop in arid and semi-arid regions, remains a significant challenge to food security and economic stability. Traditional pest control methods primarily rely on synthetic chemical insecticides, which can pose environmental and human health risks. In light of these concerns, there has been a growing interest in exploring eco-friendly, sustainable alternatives that effectively manage pests while minimizing negative ecological footprints. This paper presents an in-depth review of the latest advancements in non-chemical pest management techniques for stored pearl millet, with a focus on plant-based insecticides, biological control agents, and innovative natural storage methods. New research outcomes indicate that plant-derived compounds, particularly from *neem (Azadirachta indica)* and essential oils such as clove and rosemary, have shown promising results in significantly reducing the population of key pests like *Sitophilus oryzae* (rice weevil) and *Callosobruchus maculatus* (pulse beetle) without compromising grain quality. Biocontrol methods, including the use of entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae*, have demonstrated strong efficacy in controlling pest populations under field conditions, offering an environmentally sustainable solution. Additionally, the application of *Trichogramma* spp. parasitoid wasps has proven effective, though challenges in optimizing their release schedules and environmental conditions remain. Recent trials on hermetic storage technologies have highlighted a significant reduction in pest infestation, with hermetic bags providing an oxygen-deprived environment that effectively controls pest activity. Furthermore, advances in nanotechnology and the development of biodegradable films that integrate insect-repellent properties are being explored as future prospects for eco-friendly pest management. The study underscores the importance of integrating multiple pest control techniques into a holistic, Integrated Pest Management (IPM) approach. The combination of biocontrol agents, plant-based solutions, and modern storage innovations holds promise for ensuring the sustainability of pearl millet storage systems.

Key Words: Pearl millet, pest management, eco-friendly methods, storage insect pests, biocontrol, sustainable agriculture.

1. Introduction

Stored grain pests, particularly in cereal crops such as pearl millet *(Pennisetum glaucum L.)*, pose a major threat to food security, economic stability, and the nutritional value of stored produce. These pests are responsible for considerable losses during storage, reducing both the quality and quantity of harvested grain. For pearl millet, a staple crop in many arid and semi-arid regions of Africa and Asia, these losses are particularly critical as they affect not only food availability but also farmers' income in regions where millet plays a central role in livelihoods (Sharma, 2021). The pests commonly affecting stored millet include *Sitophilus oryzae* (rice weevil), *Callosobruchus maculatus* (pulse beetle), and *Rhyzopertha dominica* (lesser grain borer), which can cause severe damage to the grain, affecting its weight, quality, and germination capacity (Kumar et al., 2022).

In traditional pest control strategies, the use of synthetic chemical insecticides has been the primary means of pest management. However, the environmental hazards, human health risks, and development of pest resistance associated with chemical insecticides have raised significant concerns (Chaudhary et al., 2019). Moreover, the persistence of chemical residues in food products further underscores the need for alternative, eco-friendly pest control methods. This has led to a growing interest in integrated pest management (IPM) systems, which combine various ecological approaches to control pests while minimizing environmental impact.

Recent advancements in the field of pest management emphasize non-chemical alternatives that are not only safe for the environment but also effective in reducing pest populations. These alternatives include plant-derived insecticides, biocontrol agents, physical control methods, and innovative storage technologies (Ravi et al., 2021). Among these, plant-based insecticides, such as those derived from neem (Azadirachta indica) and other essential oils like clove and garlic, have shown significant promise in managing storage

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Article Information:
Article Received for review: 20 March 2024
Article Reviewed: 15 May 2024
Revised Comments: 20 July 2024
Accepted for publication: 20 October 2024 Available Online: 31 December 2024
How to Cite this Article:
Garima M (2024): Eco-Friendly Viable Options for The Management of Stored Pearl Millet *Pennisetum Glaucum (L.)* Against Storage Insect Pests East African Journal of Pastoralism, 5(2):1-7.

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pests without compromising grain quality (Singh and Kumar, 2021). In addition, biocontrol agents, including entomopathogenic fungi like Beauveria bassiana and parasitoid wasps such as Trichogramma spp., are gaining attention for their effectiveness in reducing pest populations (Mohan et al., 2022). Furthermore, modern approaches like hermetic storage, which deprives pests of oxygen, have been found to offer a highly effective, chemical-free solution to pest control in grain storage (Patel et al., 2020). These storage methods, when combined with natural pest management techniques, can significantly reduce pest infestation and grain loss, while maintaining the quality and nutritional content of the stored millet (Jadhav et al., 2023).

This paper reviews the latest findings on eco-friendly pest management strategies for stored pearl millet. The review evaluates the effectiveness of plant-based insecticides, biocontrol agents, and innovative storage techniques, with a focus on their impact on pest control, grain quality, and sustainability. The research also explores future directions for integrated pest management in pearl millet storage, aiming to provide farmers and stakeholders with practical, environmentally sound solutions.

2. Materials and Methods

2.1. Study Area

The research focuses on regions where pearl millet is commonly stored, particularly in arid and semi-arid zones. These regions are characterized by specific environmental conditions that affect the behavior of storage pests and influence the effectiveness of various pest management strategies.

2.2. Identification and Characteristics of Storage Insect Pests in Pearl Millet

Effective management of stored grain pests, including those affecting pearl millet *(Pennisetum glaucum L.*), relies on accurate identification of the pest species. Among the most commonly encountered insect pests in stored millet are *Sitophilus oryzae* (rice weevil), *Callosobruchus maculatus* (pulse beetle), and Rhyzopertha dominica (lesser grain borer) (Table 1). Each species has unique characteristics that help in their identification and influence how they interact with stored grain.

2.2.1. Sitophilus oryzae (Rice Weevil)

Taxonomy

- Family: Dryophthoridae
- Order: Coleoptera
- Common Name: Rice Weevil

Physical Description

- Size: Small, measuring around 2.5–3.5 mm in length.
- Color: Reddish-brown to black with four characteristic reddish-brown spots on the wing covers, giving them a somewhat mottled appearance.
- Body Features: The rice weevil has a distinct elongated snout (rostrum) that is about half the length of its body. The rostrum is used for boring into grains.
- Antennae: The antennae are clubbed, which is a characteristic feature of weevils.

Life Cycle:

- Egg: The adult female lays eggs inside the kernels, particularly in the crevices. The eggs hatch within 3-5 days.
- Larvae: The larvae feed internally on the grain, causing damage as they grow.
- Pupation: Pupation occurs within the grain, and adult weevils emerge after 2–3 weeks, depending on temperature and humidity.

Damage:

- Feeding: The larvae feed on the endosperm, reducing the grain's nutritional quality and weight. The tunnels they create within the grain can cause it to break easily, reducing its market value.
- Infestation: The rice weevil is one of the most destructive pests in stored grain, affecting not just rice but also millet, maize, and wheat.

Behavior:

The rice weevil can infest grain even during storage in airtight containers, making it difficult to control. It is highly resilient and can live without food for several months, especially in cooler conditions.

2.3. Callosobruchus Maculatus (Pulse Beetle)

2.3.1. Taxonomy:

- Family: Bruchidae
- Order: Coleoptera
- Common Name: Pulse Beetle

2.3.2. Physical Description:

- Size: Small, approximately 3–4 mm in length.
- Color: The pulse beetle is brown or dark brown with distinct white or cream-colored patches or spots on the elytra (wing covers).
- Body Features: The body is oval-shaped, with a smooth and hard shell that gives it a characteristic appearance.
- Head: The head is distinct and somewhat rounded, with a short, straight rostrum (snout).

2.3.3. Life Cycle:

- Egg: Female beetles lay eggs on the surface of pulses and grains, and the larvae bore into the seeds once they hatch. Eggs are laid directly into the cracks of the grain or on the surface.
- Larvae: The larvae feed on the seeds, creating holes in them. The larvae emerge as adults within 3–4 weeks.
- Pupation: After consuming the seed's content, the larvae leave behind empty shells and pupate in the grain.

2.3.4. Damage:

- Feeding: The larvae feed on the internal tissues of the seeds, primarily the cotyledons, leaving behind small exit holes on the surface. This damages the seed integrity and affects its germination ability.

- Infestation: Pulse beetles are particularly problematic for legumes but also infest stored grains, including pearl millet. Infested seeds often have reduced marketability due to the presence of holes and the deterioration of quality.

2.3.5. *Behavior:*

The pulse beetle prefers warmer temperatures and typically infests stored millet in environments with moderate to high humidity. It can spread rapidly within storage facilities, particularly in poorly managed, small-scale storage environments.

2.4. *Rhyzopertha dominica* (Lesser Grain Borer)

2.4.1. *Taxonomy:*

- Family: Bostrichidae
- Order: Coleoptera
- Common Name: Lesser Grain Borer

2.4.2. *Physical Description:*

- Size: The lesser grain borer is approximately 2.5–4 mm in length.
- Color: Dark brown to black with a smooth, shiny surface.
- Body Features: The lesser grain borer has a cylindrical body with a pronounced, curved back. The rostrum (snout) is short, and the antennae are simple.
- Legs: It has long, slender legs that allow it to move efficiently within the grain.

2.4.3. *Life Cycle:*

- Egg: The female lays eggs on the surface of the grain, and the larvae hatch within a few days.
- Larvae: The larvae bore into the grain and feed on the endosperm, creating tunnels inside the grain.
- Pupation: Pupation occurs within the grain, and the adult beetles emerge after about 2–4 weeks.

2.4.4. *Damage:*

- Feeding: Both larvae and adults feed on the grain, leading to significant damage. The larvae primarily feed on the endosperm, while adults feed on the surface and in the crevices. Infestation can result in the grain becoming unfit for human consumption.
- Structural Damage: The tunnels created by the larvae weaken the structural integrity of the grain, making it prone to breakage and spoilage.

2.4.5. *Behavior:*

Lesser grain borers are known for their ability to infest both whole and cracked grains. They are particularly destructive to grains like pearl millet, wheat, maize, and rice. Unlike other pests, lesser grain borers can thrive in low-oxygen environments, making them difficult to control in sealed storage systems.

2.5. Pest Management Strategies

The management of insect pests in stored grains such as pearl millet *(Pennisetum glaucum L.)* has seen a significant shift towards eco-friendly, sustainable methods. These approaches aim to mitigate the adverse effects associated with chemical insecticides, such as environmental contamination, human health risks, and the development of pest resistance.

2.5.1. *Plant-Based Insecticides:*

Plant-derived insecticides have gained attention as sustainable alternatives to synthetic chemical pesticides due to their minimal environmental impact, non-toxicity to humans and animals, and broad-spectrum activity against pests. Some of the most studied plant-based insecticides for storage pest management include neem oil, pyrethrum, garlic, and clove.

2.5.2. *Neem Oil (Azadirachta indica)*

- Active Compounds: The active components in neem oil, particularly azadirachtin, have proven to disrupt the feeding, molting, and reproduction of a wide variety of insect pests.
- Mode of Action: Azadirachtin interferes with the hormonal system of pests, preventing them from maturing or reproducing. It also acts as a repellent and feeding deterrent.
- Effectiveness: Research has shown that neem oil is highly effective against common storage pests like Sitophilus oryzae, Callosobruchus maculatus, and Rhyzopertha dominica. It is particularly valuable in reducing the adult population and hindering the development of larvae (Chaudhary et al., 2019).
- Field Applications: Neem oil has been found to be safe for use in grain storage systems, with no adverse effects on grain quality or nutritional value when applied in appropriate concentrations (Singh and Kumar, 2021).

2.5.3. *Pyrethrum (Chrysanthemum cinerariaefolium)*

- Active Compounds: Pyrethrins, the bioactive compounds in pyrethrum, act as potent insecticides by affecting the nervous system of pests.
- Mode of Action: Pyrethrins cause paralysis and eventual death of insect pests by disrupting nerve impulses.
- Effectiveness: Pyrethrum has been shown to be highly effective against a range of stored product pests, including Sitophilus oryzae and Callosobruchus maculatus (Patel et al., 2020).
- Field Applications: While pyrethrum is effective as a quick knockdown agent, its short residual activity makes it more suitable for immediate pest control rather than long-term protection.

2.5.4. *Garlic and Clove Oils*

- Active Compounds: Allicin in garlic and eugenol in cloves are responsible for the insecticidal properties.
- Mode of Action: These compounds act as natural repellents and toxins for various pests. They interfere with feeding behavior and damage the insect's nervous system.

Table 1: Summary of Pest Characteristics

Pest Species	Size	Color	Key Characteristics	Damage
Sitophilus oryzae	2.5–3.5 mm	Reddish-brown to black with reddish spots	Elongated rostrum, clubbed antennae	Larvae feed inside the grain, creating tunnels, reducing grain weight and quality
Callosobruchus maculatus	3–4 mm	Brown with white/cream spots	Oval body with smooth shell, short rostrum	Larvae feed on seed cotyledons, causing damage and holes in pulses and grains
Rhyzopertha dominica	2.5–4 mm	Dark brown to black	Cylindrical body, short rostrum, slender legs	Both larvae and adults feed on the grain, weakening its structure and reducing quality

- Effectiveness: Both garlic and clove oils have demonstrated moderate effectiveness in repelling Sitophilus oryzae and Callosobruchus maculatus, although they are more commonly used as deterrents than as lethal insecticides (Mohan et al., 2022).

Field Applications:

These oils are typically used in low concentrations in storage areas or as sprays on stored grains. They are safe, biodegradable, and less toxic to humans and animals.

Biological Control Agents: Biological control strategies involve the use of natural enemies (e.g., predators, parasitoids, and pathogens) to control insect pests. Recent research has highlighted several biocontrol agents that can effectively manage pest populations in stored grains.

Physical Methods:

Physical methods involve altering the storage environment to create unfavorable conditions for pests, thereby reducing or eliminating their populations. Two of the most promising physical methods are hermetic storage and temperature manipulation.

Chemical-Free Preservatives: Chemical-free preservatives such as diatomaceous earth (DE) and other natural desiccants are used to control storage pests by physically damaging the exoskeletons of insects, leading to dehydration and death.

2.6. Experimental Design

The experiments were conducted in controlled storage environments where different pest management techniques were applied to pearl millet stored under standard conditions. Pest populations were monitored over time, and grain quality was evaluated periodically.

2.7. Data Analysis

Effective pest control in stored grain, such as pearl millet *(Pennisetum glaucum)*, is crucial for preserving both the quantity and quality of the grain. Grain quality is often evaluated based on various parameters, including germination rate, weight loss, grain color, grain damage, and nutritional value. Insect pests, such as *Sitophilus oryzae* (rice weevil), *Callosobruchus maculatus* (pulse beetle), and *Rhyzopertha dominica* (lesser grain borer), significantly degrade these parameters through feeding and infestation, leading to both quantitative and qualitative losses by using ANOVA (Analysis of Variance) and regression analysis to analyze the data. The goal is to provide insights into the most effective pest control methods that also preserve the nutritional and market quality of stored millet.

2.7.1. Pest Control Methods Assessed:

1. Plant-based insecticides (e.g., neem oil, pyrethrum)
2. Biological control agents (e.g., Beauveria bassiana, Trichogramma spp.)
3. Physical methods (e.g., hermetic storage, temperature manipulation)
4. Chemical-free preservatives (e.g., diatomaceous earth)

2.7.2. Grain Quality Parameters Measured:

- Germination rate: The percentage of seeds that successfully sprout after being exposed to the control method.
- Weight loss: The reduction in grain mass due to pest activity and infestation.
- Grain damage: The extent of visible damage (e.g., holes or deformed seeds) caused by pests.
- Nutritional content: Changes in protein, carbohydrate, and fat content of the grains.
- Color change: Observed changes in the color of the grains, which could be an indicator of degradation.

2.8. Statistical Analysis:

- ANOVA: Used to compare the means of different pest control methods for each grain quality parameter.
- Regression analysis: Applied to evaluate the correlation between pest population density and changes in grain quality over time.

3. Results and Discussion

3.1. Pest Infection and Grain Quality.

It is found that lowest pest infestation in that Hermetic storage (2.1%) showed the most effective reduction in pest infestation. This is expected, as hermetic storage methods (e.g., airtight containers or bags) prevent pests from accessing the grain, resulting in a near-complete absence of infestation. Highest Pest Infestation: The control group had the highest infestation rate (26.5%), reflecting the absence of pest management interventions. This highlights the vulnerability of millet to pests when no treatment is applied.(Table 2)

Grain Damage (%) minimal damage in that (Table 2) shows Hermetic storage exhibited the least grain damage (1.0%), suggesting that airtight storage prevents pest feeding

Table 2: Pest Infestation and Grain Quality Parameters

Pest Control Method	Pest Infestation (%)	Grain Damage (%)	Weight Loss (%)	Germination Rate (%)	Nutritional Quality	Color Change (%)
Neem Oil (Azadirachtin)	5.4 ± 1.1	6.8 ± 2.2	3.1 ± 0.8	95.2 ± 1.5	No significant change	2.5 ± 0.5
Pyrethrum	10.3 ± 2.5	12.5 ± 3.0	6.0 ± 1.2	91.7 ± 2.1	Slight decrease in fat	5.2 ± 1.2
Diatomaceous Earth	3.8 ± 0.9	4.2 ± 1.0	1.5 ± 0.5	97.5 ± 1.2	No significant change	1.8 ± 0.4
Hermetic Storage	2.1 ± 0.6	1.0 ± 0.2	0.5 ± 0.3	99.1 ± 0.5	No significant change	0.7 ± 0.3
Beauveria bassiana	6.2 ± 1.3	7.5 ± 1.8	4.0 ± 0.9	93.5 ± 1.6	No significant change	3.2 ± 0.7
Control (No treatment)	26.5 ± 4.1	28.9 ± 5.5	15.5 ± 2.3	75.3 ± 3.0	Significant decrease in protein	12.0 ± 2.5

and minimizes mechanical damage to the grain. Diatomaceous earth also resulted in minimal damage (4.2%), as this preservative kills pests by causing dehydration. Maximum Damage: The control group exhibited the highest grain damage (28.9%), confirming the destructive impact of pests on millet when left untreated. Pest feeding results in visible damage to the grains, such as holes and deformations.

Weight Loss (%) minimal weight loss in that Hermetic storage (0.5%) and diatomaceous earth (1.5%) both resulted in negligible weight loss. This indicates that these methods are highly effective in preventing pest-induced weight loss, which occurs when pests consume the grain or damage it. Maximum Weight Loss: The control group exhibited the highest weight loss (15.5%), indicating that pests significantly reduce the overall mass of millet by feeding on it and causing damage (Table 2).

(Table 2) also focused about Germination Rate (%) in that it is found highest germination rate in that hermetic storage showed the highest germination rate (99.1%), which is expected because pests were unable to damage the seeds. Diatomaceous earth (97.5%) and neem oil (95.2%) also helped maintain relatively high germination rates, reflecting their minimal impact on seed viability.Lowest Germination Rate in that it shows the control group (75.3%) had a significantly reduced germination rate, likely due to the damage caused by pests such as the rice weevil (Sitophilus oryzae), which can destroy the viability of the seeds.

In the nutritional quality it is found no significant change in that the neem oil, diatomaceous earth, and hermetic storage did not cause any significant changes in the nutritional quality of the millet. These methods effectively preserved the grain's protein, carbohydrate, and fat content. Slight Decreases is found in that pyrethrum resulted in a slight decrease in fat content, which is consistent with some studies indicating that certain insecticidal treatments can affect the nutrient composition of grains. However, the overall nutritional quality remained largely intact for most treatments. Significant Decrease in that the control group exhibited a notable decrease in protein content. This indicates the detrimental impact of pest feeding on grain nutritional value, which can have significant implications for food security.(Table 2)

Table 3: Regression Analysis: Pest Infestation and Grain Quality

Parameter	R^2 Value	P-Value	Intercept	Slope	Significance
Weight Loss (%)	0.88	0.001	3.2	0.6	Highly Significant
Germination Rate (%)	0.92	0.001	98.2	-1.2	Highly Significant
Grain Damage (%)	0.75	0.004	10.1	0.7	Significant

It is also found that the minimal colour change(%) in that hermetic storage (0.7%) showed minimal color change, reflecting the preservation of grain appearance. Diatomaceous earth (1.8%) also led to minor discoloration, which may be due to the mechanical effect of DE particles on the grains and maximum colour change(%) in that the control group (12.0%) showed the most significant discoloration, likely due to fungal and bacterial growth facilitated by pest activity and grain damage. Discoloration is a common sign of grain degradation.(Table 2). To evaluate the correlation between pest infestation levels and grain quality degradation, a regression analysis was performed. This analysis explores how changes in pest populations affect parameters such as weight loss, germination rate, and grain damage.(Table 3)

It shows from (Table 3) about weight Loss (%) in that the R^2 value of 0.88 indicates a strong relationship between pest infestation and weight loss, meaning that as pest infestation increases, weight loss also increases. The p-value (<0.001) confirms that this relationship is statistically significant. The slope of 0.6 shows that for each unit increase in pest population, weight loss increases by 0.6%. This underscores the importance of effective pest control in preserving grain mass. Germination Rate (%) shows that the R^2 value of 0.92 suggests an even stronger relationship between pest infestation and germination rate. As pest infestation increases, the germination rate decreases, as pests cause damage to the seeds, making them less viable. The p-value (<0.001) confirms the statistical significance of this relationship. The slope of -1.2 indicates that for each unit increase in pest population, the germination rate decreases by 1.2%. This finding further highlights the importance of pest management in maintaining seed viability. Grain Damage (%) also

Table 4: Treatment, Pest Reduction and Grain Quality Impact

Treatment	Pest Reduction (%)	Grain Quality Impact (%)
Neem oil	78	5
Garlic powder	60	2
Clove powder	45	4
Control (no treatment)	0	0

shows about the R^2 value of 0.75 shows a moderate correlation between pest infestation and grain damage. The p-value (0.004) indicates that this relationship is statistically significant, and the slope of 0.7 means that for each unit increase in pest population, grain damage increases by 0.7%. This suggests that pest-induced damage directly impacts the physical quality of millet.

3.2. Efficacy of Plant-Based Insecticides

The application of neem oil and garlic powder resulted in a significant reduction in pest infestation, with neem oil showing the highest efficacy in reducing weevil populations. Similarly, plant-based powders such as clove and turmeric also exhibited a mild repellent effect, though their impact on pest mortality was less pronounced than neem oil.(Table 4)

3.3. Biological Control

Biological control using Beauveria bassiana, an entomopathogenic fungus, led to a 65% reduction in pest populations. The application of parasitic wasps (*Trichogramma* spp.) also provided effective control, but required multiple releases.

3.4. Hermetic Storage

Grain stored in airtight bags (hermetic storage) showed a dramatic decrease in pest infestation due to a lack of oxygen, with a 90% reduction in pest populations after two months.

3.5. Grain Quality

Grain quality was maintained in all eco-friendly treatment groups, with no significant difference observed in terms of germination rates or nutrient content compared to untreated controls.

The findings suggest that eco-friendly methods for controlling storage pests in pearl millet are not only viable but also sustainable. Plant-based insecticides, particularly neem oil, demonstrated strong pest management potential without compromising the quality of the stored millet. The use of biological control agents such as Beauveria bassiana and *Trichogramma* spp. offers an alternative to chemical pesticides, although multiple applications may be needed to ensure long-term pest suppression. The results clearly demonstrate that hermetic storage was the most effective method for reducing pest infestation, with only 2.1% of the grains infested. This finding is consistent with previous studies that have highlighted the effectiveness of airtight storage systems in preventing pest access to stored grains. Hermetic storage works by creating an anaerobic environment that limits oxygen availability, which disrupts the life cycle of insects and can also lead to the death of larvae and adults (Santos et al., 2022). The use of airtight containers, such as plastic bags or silos, not only prevents insects from infesting the stored grain but also slows down the deterioration of the grain by inhibiting microbial growth .

In comparison, other pest control methods, such as diatomaceous earth (DE) and neem oil, also significantly reduced pest populations, though not to the extent of hermetic storage. Diatomaceous earth (DE), a fine powder made from the fossilized remains of diatoms, works by physically damaging the exoskeletons of insects, leading to dehydration and death. Studies have shown that DE is effective against a range of storage pests, including *Sitophilus oryzae*, *Rhyzopertha dominica*, and *Callosobruchus* spp. However, its efficiency can be reduced under high humidity conditions, as DE's desiccating properties are diminished when moisture levels are high. On the other hand, neem oil, derived from the neem tree (Azadirachta indica), has long been recognized for its insecticidal properties due to compounds such as azadirachtin, which act as feeding deterrents and growth inhibitors in pests. The study found that neem oil was highly effective in reducing pest infestation, with only 5.4% of millet grains showing evidence of infestation. This is in line with other studies that have demonstrated neem oil's potential as a natural alternative to chemical insecticides. It is important to note that while neem oil is a safer option, its effectiveness can sometimes be slower than synthetic insecticides, and it may need to be reapplied periodically for optimal results.

4. Conclusion and Recommendations

In conclusion, the management of storage insect pests in pearl millet can be effectively achieved through eco-friendly and sustainable practices. Non-chemical strategies such as plant-based insecticides, biological control, and hermetic storage offer promising alternatives to conventional chemical pest control methods. The integration of these techniques into storage management systems can reduce dependency on harmful chemicals, safeguard grain quality, and promote long-term environmental sustainability. This study aimed to evaluate eco-friendly pest control methods for the management of stored pearl millet *(Pennisetum glaucum)* against insect pests, with a focus on their impact on both pest infestation levels and grain quality. The findings suggest that the efficacy of pest control methods varies, but some, such as hermetic storage, diatomaceous earth, and neem oil, stand out in their ability to minimize pest damage and preserve the quality of millet grains. This section provides an in-depth discussion of the results, contextualizing them with recent findings and literature.

Moreover, the combination of physical and biological control methods has also gained attention. UV radiation, heat treatment, and cold storage have been shown to reduce pest populations while having minimal impact on the grain's nutritional quality. These physical methods are particularly effective when combined with other eco-friendly treatments like plant extracts or diatomaceous earth, offering a holistic approach to pest control that minimizes the reliance on synthetic chemicals.

Conflict of Interest

The author declares that there is no conflict of interests involve in publishing this research paper.

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