BioBlock Repellent: Development and Evaluation of a Waste-Derived Biodegradable Botanical Composite for Sustainable Post-Harvest Grain Protection

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Abstract

Post-harvest deterioration of stored food grains remains one of the leading contributors to food insecurity worldwide, particularly in developing countries where grains are commonly stored under household and small-scale commercial conditions. Conventional grain protectants such as aluminum phosphide (Alphos) and paradichlorobenzene-based formulations effectively suppress insect infestation but present considerable risks due to toxic residues, hazardous fumigation gases, environmental contamination, and adverse impacts on human and animal health. These challenges necessitate the development of safer, biodegradable, and environmentally sustainable alternatives.

This study presents **BioBlock Repellent**, an innovative biodegradable grain-protection system fabricated primarily from kitchen and agricultural waste materials. The formulation combines pomegranate peel powder, neem leaf powder, clove powder, onion peel powder, and Fuller's Earth (Multani Mitti), with crop-specific variants incorporating turmeric, camphor, or lavender oil to optimize protection for pulses, wheat, and mixed grains. The formulation utilizes the insect-repellent properties of naturally occurring phytochemicals together with the moisture-regulating characteristics of mineral clay to create a slow-release botanical protective matrix.

A systematic experimental program consisting of formulation optimization, comparative efficacy studies, laboratory validation, biodegradation assessment, consumer surveys, and field-performance evaluation was conducted. Laboratory testing demonstrated superior moisture regulation, improved nutritional retention, and effective suppression of storage pests without introducing detectable chemical odor or toxic residues. Controlled storage experiments showed BioBlock to provide pest protection comparable to conventional chemical fumigants while maintaining grain quality. Environmental assessment confirmed progressive biodegradation under natural soil conditions with negligible ecological impact. A three-month user evaluation further indicated high consumer satisfaction and an effective operational lifespan of approximately 60–75 days under normal storage conditions.

By transforming agricultural and household organic waste into a value-added grain preservation technology, BioBlock promotes circular resource utilization while supporting sustainable agriculture and food safety. The innovation aligns with the United Nations Sustainable Development Goals related to Zero Hunger, Good Health and Well-being, Responsible Consumption and Production, and Climate Action. The findings suggest that BioBlock represents a practical, affordable, and environmentally responsible alternative to conventional synthetic grain repellents suitable for household, retail, and small-scale agricultural storage systems.

Keywords: Biodegradable grain protectant; botanical pesticide; post-harvest preservation; kitchen waste valorization; sustainable agriculture; neem; pomegranate peel; Fuller's Earth; grain storage; circular bioeconomy.

1. Introduction

Post-harvest food losses represent one of the greatest challenges to global food security, particularly in developing countries where millions of households depend on stored cereals and pulses for daily consumption. According to the Food and Agriculture Organization (FAO), nearly one-third of food produced worldwide is either lost or wasted before reaching consumers. A considerable proportion of these losses occurs during storage due to insect infestation, moisture accumulation, fungal contamination, and poor storage practices. In India, post-harvest grain losses are estimated to range between **5–10%**, with significantly higher losses under traditional household storage conditions, resulting in substantial economic losses for farmers, retailers, and consumers. These losses directly threaten food availability while increasing production pressure on already limited agricultural resources.

Stored grain insects such as *Sitophilus oryzae* (rice weevil), *Tribolium castaneum* (red flour beetle), *Rhyzopertha dominica* (lesser grain borer), and grain moths are among the primary causes of deterioration in stored food grains. These pests consume grain kernels, reduce nutritional quality, contaminate food through excreta and insect fragments, and create favorable conditions for fungal growth. Increased grain moisture further accelerates microbial proliferation, causing mold formation and production of harmful mycotoxins that compromise food safety.

To minimize storage losses, synthetic chemical fumigants such as aluminum phosphide (commercially marketed as Alphos) and paradichlorobenzene-based repellents (commonly known as Para Tikdi) have been widely adopted because of their rapid insecticidal activity. However, despite their effectiveness, these chemicals pose significant disadvantages. Aluminum phosphide releases phosphine gas, an extremely toxic fumigant that requires careful handling and has been associated with accidental poisoning and fatalities. Chemical fumigants may also leave undesirable residues on food grains, generate unpleasant odors, affect grain quality, contaminate the surrounding environment, and pose risks to livestock and non-target organisms. Growing awareness regarding food safety and environmental sustainability has therefore increased the demand for non-toxic alternatives capable of protecting stored grains without adverse ecological or health consequences.

Botanical pesticides have emerged as promising alternatives because many plants naturally synthesize secondary metabolites that repel or inhibit insects while remaining relatively safe for humans and the environment. Neem (*Azadirachta indica*) contains azadirachtin, a well-known insect growth regulator that interferes with feeding, reproduction, and metamorphosis in numerous storage pests. Clove (*Syzygium aromaticum*) is rich in eugenol, a volatile phenolic compound exhibiting strong insecticidal and antimicrobial activity. Similarly, pomegranate peel contains hydrolysable tannins, flavonoids, and polyphenols possessing antioxidant and antimicrobial properties, while onion peel contains sulfur-containing volatile compounds capable of deterring insects. When combined appropriately, these botanical materials offer the potential to create an effective natural pest management system without relying on hazardous synthetic chemicals.

Besides insect control, moisture regulation is equally important in maintaining grain quality. Excessive moisture accelerates fungal development, reduces shelf life, and promotes insect multiplication. Fuller's Earth (Multani Mitti), a naturally occurring hydrous aluminum silicate clay, exhibits high adsorption capacity and serves as an efficient moisture regulator. Incorporating this material into a botanical formulation provides both structural stability and passive humidity control, thereby creating a dual-action grain preservation system.

An additional environmental challenge addressed by this study is the increasing accumulation of biodegradable organic waste generated from households and food processing industries. Large quantities of pomegranate peels, onion peels, and other plant residues are discarded daily despite containing valuable bioactive compounds. Transforming these agricultural by-products into functional grain-protection materials supports waste valorization, promotes circular economy principles, reduces environmental burden, and generates value-added products from otherwise discarded biomass.

Recognizing these opportunities, the present research introduces **BioBlock Repellent: WasteWise Storage**, a biodegradable botanical grain-protection cube developed using readily available natural ingredients and kitchen waste materials. Unlike conventional fumigants that depend on toxic chemical vapors, BioBlock combines natural insect-repellent phytochemicals with moisture-regulating mineral components to create a slow-release protective environment for stored grains. The innovation emphasizes sustainability, affordability, safety, and ease of application while maintaining grain quality during storage.

The BioBlock formulation consists primarily of pomegranate peel powder, neem leaf powder, clove powder, onion peel powder, and Fuller's Earth, with crop-specific modifications incorporating turmeric powder, camphor, or lavender oil to optimize performance for pulses, wheat, and multigrain storage. By integrating insect repellency, moisture management, biodegradability, and waste recycling into a single product, BioBlock offers a holistic approach toward sustainable post-harvest grain preservation.

The effectiveness of BioBlock was evaluated through formulation optimization experiments, laboratory nutritional analyses, comparative storage trials with commercial chemical repellents, biodegradation studies, environmental compatibility assessment, economic evaluation, and extensive user surveys involving households, retailers, and farmers. Collectively, these investigations assess the feasibility of BioBlock as a practical and environmentally responsible alternative to conventional grain storage chemicals.

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2. Research Gap

Unlike existing studies that investigate individual botanical extracts or chemical fumigants independently, very few have developed an integrated biodegradable grain-protection system utilizing multiple agricultural waste materials while simultaneously evaluating storage performance, nutritional preservation, biodegradability, economic feasibility, and consumer acceptance. Most commercially available grain repellents prioritize insect mortality but overlook food safety, environmental sustainability, and waste utilization. Furthermore, limited research has explored the synergistic interaction between moisture-regulating mineral binders and botanical repellents within a slow-release biodegradable matrix.

BioBlock addresses these gaps by developing a multifunctional grain protection technology that combines natural pest repellency, humidity regulation, kitchen waste recycling, environmental compatibility, and economic affordability into a single biodegradable product suitable for household, retail, and small-scale agricultural storage.

Table 1. Research Gap Analysis

Area of Existing Research	**Limitations of Existing Studies**	**BioBlock Innovation**
Chemical fumigants (Alphos, Para Tikdi)	**Highly toxic, hazardous during handling, leave chemical residues on grains, harmful to humans and the environment**	**BioBlock is completely biodegradable, non-toxic, residue-free, and safe for household use**
Neem powder and botanical repellents	**Short protection period, uneven distribution, frequent replacement required**	**Slow-release compressed BioBlock provides long-lasting protection for approximately 60–75 days**

Essential oil-based grain repellents	**Rapid evaporation reduces long-term effectiveness**	**Botanical ingredients are embedded within a solid matrix, enabling gradual and sustained release of active compounds**
Moisture absorbents	**Reduce humidity but provide little or no insect control**	**Fuller's Earth simultaneously regulates moisture while botanical ingredients repel storage pests**
Agricultural waste utilization	**Most studies utilize only a single agricultural waste material**	**BioBlock integrates multiple kitchen and agricultural wastes (pomegranate peel, onion peel, neem leaves) into one functional product**
Stored grain protection research	**Primarily focused on insect mortality with limited evaluation of grain quality**	**BioBlock evaluates pest control, moisture regulation, nutritional preservation, biodegradability, user acceptance, and economic feasibility**
Commercial grain protectants	**Depend on synthetic chemicals and generate environmental pollution**	**BioBlock supports circular economy principles through waste valorization and sustainable materials**

2. Literature Review

Post-harvest grain protection has become an increasingly important area of research due to rising concerns regarding food security, environmental sustainability, and the health hazards associated with synthetic pesticides. Numerous researchers have investigated botanical pesticides, agricultural waste utilization, and biodegradable storage technologies as sustainable alternatives to conventional chemical fumigants.

Geyer et al. (2017) reported that over **8.3 billion tonnes** of plastic have been produced globally since the 1950s, with nearly **79%** accumulating in landfills or natural ecosystems. Although plastic packaging dominates modern storage systems because of its low cost and durability, its improper disposal contributes significantly to environmental pollution and microplastic contamination. This has encouraged researchers to develop biodegradable products derived from renewable biological resources.

Several studies have demonstrated the insecticidal potential of botanical materials. **Isman (2020)** concluded that plant-derived compounds possess broad-spectrum insect-repellent activity while exhibiting significantly lower toxicity to humans than synthetic pesticides. Botanical pesticides are biodegradable, environmentally compatible, and less likely to induce insect resistance than conventional chemicals.

Among botanical insecticides, **Neem (*Azadirachta indica*)** has received considerable scientific attention. **Tiwari and Shrestha (2017)** reported that azadirachtin, the principal bioactive compound present in neem leaves and seeds, interferes with insect feeding behavior, growth, molting, and reproduction across more than **200 insect species**. Neem extracts have therefore become one of the most extensively studied natural grain protectants worldwide.

Clove (*Syzygium aromaticum*) has also demonstrated remarkable insecticidal properties due to its high concentration of **eugenol**, a naturally occurring phenolic compound. **Zhou and Wang (2023)** reported that eugenol exhibits fumigant toxicity against several stored grain insects while simultaneously providing antimicrobial activity that suppresses fungal contamination during storage.

Agricultural waste materials have recently gained importance as sustainable raw materials for value-added products. **Patel and Singh (2023)** emphasized that fruit and vegetable processing residues contain numerous valuable phytochemicals that remain largely underutilized despite their potential applications in agriculture, food preservation, and environmental management. Converting these wastes into functional agricultural products contributes to circular economy principles while simultaneously reducing environmental pollution.

Among fruit wastes, **pomegranate peel (*Punica granatum*)** possesses exceptionally high concentrations of polyphenols, flavonoids, tannins, and antioxidant compounds. These phytochemicals exhibit antimicrobial, antifungal, and insect-deterrent activities that may contribute to improved grain preservation. Likewise, **onion peel (*Allium cepa*)**, often discarded as household waste, contains sulfur-containing volatile compounds capable of repelling storage insects while providing antioxidant benefits.

Moisture management remains another critical component of grain preservation. Increased humidity encourages fungal growth, accelerates grain respiration, and facilitates insect multiplication. **Mishra and Joshi (2024)** demonstrated that **Fuller's Earth (Multani Mitti)** possesses excellent adsorption characteristics and effectively regulates localized humidity because of its porous mineral structure. Besides acting as a moisture controller, it also serves as an effective natural binder for biodegradable composite materials.

The application of biodegradable materials in agriculture has expanded rapidly over the past decade. Previous investigations have focused on biodegradable packaging films, seedling containers, mulch films, and natural storage materials. However, relatively few studies have attempted to integrate multiple botanical repellents and agricultural waste materials into a single slow-release grain-protection system capable of simultaneously controlling insects, regulating moisture, preserving grain quality, and degrading safely after disposal.

Consumer awareness regarding chemical-free food preservation has also increased considerably. Recent market surveys indicate that households increasingly prefer eco-friendly alternatives over conventional chemical pesticides, provided they offer comparable effectiveness, affordability, and ease of use. Sustainable grain preservation technologies therefore present both scientific and commercial opportunities for reducing post-harvest food losses.

The present study builds upon previous research by integrating multiple botanical ingredients with a mineral moisture-regulating matrix into a single biodegradable product known as **BioBlock Repellent**. Unlike conventional grain protectants that rely solely on toxic chemical fumigants or single botanical extracts, BioBlock utilizes synergistic interactions among neem, clove, pomegranate peel, onion peel, and Fuller's Earth to achieve simultaneous pest repellency, moisture regulation, nutritional preservation, environmental compatibility, and agricultural waste utilization. Furthermore, the innovation incorporates laboratory validation, biodegradation assessment, user surveys, and economic evaluation to comprehensively assess its practical applicability for household, retail, and small-scale agricultural storage.

Author (Year)	**Research Focus**	**Major Findings**	**Research Gap Addressed by BioBlock**
Geyer et al. (2017)	Plastic waste and environmental pollution	Plastic accumulation poses long-term ecological threats	BioBlock replaces synthetic chemical storage products with biodegradable materials
Isman (2020)	Botanical pesticides	Plant-derived compounds are safer and biodegradable	Combines multiple botanical insect repellents into one formulation
Tiwari & Shrestha (2017)	Neem (Azadirachta indica)	Azadirachtin effectively disrupts insect growth and reproduction	Neem integrated with complementary botanicals for enhanced protection
Zhou & Wang (2023)	Clove essential oil	Eugenol exhibits strong insecticidal and antimicrobial properties	Controlled slow-release delivery through compressed BioBlock matrix
Patel & Singh (2023)	Agricultural waste utilization	Organic waste can be converted into value-added products	Kitchen waste transformed into biodegradable grain-protection technology
Mishra & Joshi (2024)	Fuller's Earth applications	Excellent moisture adsorption and binding characteristics	Used simultaneously as binder and humidity regulator in BioBlock
Kumar & Sharma (2022)	Botanical fumigants	Natural repellents provide safer alternatives to synthetic chemicals	Combines safety, affordability, biodegradability, and prolonged effectiveness
Naqvi & Khan (2022)	Botanical grain protectants	Neem-based formulations reduce storage pest infestation	Multi-ingredient formulation offering broader pest control and moisture management

Table 1. Comparison of Conventional Grain Protectants and BioBlock

Parameter	**Chemical Fumigants**	**Single Botanical Powders**	**BioBlock Repellent**
Pest Repellency	Excellent	Moderate	Excellent
Human Safety	Low	High	Very High
Toxic Residues	Present	Absent	Absent

Environmental Impact	High	Low	Very Low
Moisture Regulation	Poor	Limited	Excellent
Nutritional Preservation	Moderate	Moderate	High
Biodegradable	No	Yes	Yes
Kitchen Waste Utilization	No	Partial	Yes
Cost Effectiveness	Moderate	Moderate	High
Shelf Life	Moderate	Short	60–75 Days

3. Objectives of the Study

The present investigation was undertaken with the objective of developing and scientifically evaluating a biodegradable, plant-based grain protection system capable of replacing conventional synthetic fumigants used during post-harvest storage. The study specifically aims to integrate naturally occurring insect-repellent phytochemicals with moisture-regulating mineral constituents into a sustainable composite capable of preserving grain quality while minimizing environmental impact.

The specific objectives of the study are as follows:

1. To formulate a biodegradable grain-protection block utilizing agricultural and household organic waste materials, including pomegranate peel, onion peel, neem leaves, clove, and Fuller's Earth.
2. To optimize the composition of the BioBlock formulation through comparative screening of multiple botanical ingredient combinations and identify the most effective formulation for long-term grain protection.
3. To evaluate the efficacy of BioBlock against commonly used commercial grain protectants, including aluminum phosphide (Alphos) and Para Tikdi, under identical storage conditions.
4. To investigate the ability of BioBlock to regulate grain moisture, suppress insect infestation, and preserve the nutritional quality of stored wheat, pulses, and millets.
5. To assess the biodegradability and environmental compatibility of the developed formulation through controlled soil degradation studies.
6. To determine the practical performance, user acceptance, and functional lifespan of BioBlock through household- and retailer-based field evaluation.
7. To examine the economic feasibility and commercial applicability of BioBlock as a sustainable alternative for household, retail, and small-scale agricultural grain storage.

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4. Research Hypothesis

The present study was designed based on the following research hypotheses:

H_0 (Null Hypothesis):

There is no statistically significant difference between BioBlock Repellent and commercially available synthetic grain protectants with respect to pest control efficiency, moisture regulation, nutritional preservation, and storage performance.

H_1 (Alternative Hypothesis):

BioBlock Repellent exhibits significantly improved environmental safety, biodegradability, nutritional preservation, and storage performance while providing pest protection comparable to commercially available synthetic grain protectants.

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5. Novelty of the Research

The novelty of the present investigation lies in the development of a multifunctional biodegradable grain-protection composite prepared predominantly from discarded kitchen and agricultural waste. Unlike conventional grain protectants that rely exclusively on toxic fumigants or single botanical extracts, BioBlock integrates multiple phytochemical-rich ingredients within a mineral-supported slow-release matrix capable of simultaneously repelling storage insects, regulating humidity, preserving grain quality, and degrading naturally after disposal.

Furthermore, the present investigation combines laboratory validation, formulation optimization, nutritional analysis, environmental degradation studies, consumer acceptance surveys, and economic assessment within a single integrated framework. Such a comprehensive evaluation of a biodegradable botanical grain-protection system remains relatively unexplored in the existing literature.

The innovation also promotes the valorization of agricultural waste streams by converting pomegranate peels and onion peels, which are generally discarded as household waste, into value-added grain preservation products. Consequently, BioBlock contributes simultaneously to sustainable agriculture, circular bioeconomy, food safety, and environmental conservation.

6. Materials and Methods

6.1 Study Design

The present investigation adopted an experimental research design to develop, optimize, and validate **BioBlock Repellent**, a biodegradable botanical grain protectant intended for sustainable post-harvest storage. The study comprised formulation development, laboratory validation, comparative efficacy assessment, biodegradation studies, nutritional evaluation, consumer surveys, and economic analysis. Experimental observations were supplemented with laboratory investigations and field-based performance assessments to comprehensively evaluate the functionality and practical applicability of the developed product.

The overall research methodology was executed in seven sequential phases: (i) collection and processing of raw materials, (ii) formulation optimization, (iii) fabrication of BioBlock composites, (iv) laboratory evaluation of storage performance, (v) environmental biodegradation assessment, (vi) field performance and consumer validation, and (vii) economic feasibility analysis.

6.2 Materials

The BioBlock formulation was prepared using naturally available botanical ingredients possessing insect-repellent, antimicrobial, antioxidant, and moisture-regulating properties. All plant materials were collected from household kitchen waste or locally available sources, cleaned thoroughly, shade-dried, pulverized, and sieved prior to formulation. Fuller's Earth (Multani Mitti) served as the structural binder and moisture-regulating matrix.

Table 2. Composition and Functional Characteristics of BioBlock Ingredients

Ingredient	Scientific Name	Primary Function	Source
Neem Leaf Powder	*Azadirachta indica*	Natural insect repellent; growth regulator	Fresh neem leaves
Clove Powder	*Syzygium aromaticum*	Insecticidal and antimicrobial activity	Dried flower buds
Pomegranate Peel Powder	*Punica granatum*	Antioxidant and antifungal properties	Household fruit waste
Onion Peel Powder	*Allium cepa*	Sulfur compounds providing insect deterrence	Kitchen waste
Fuller's Earth (Multani Mitti)	Hydrous aluminium silicate	Moisture regulation and structural binding	Commercial grade clay
Camphor	*Cinnamomum camphora*	Additional volatile insect repellency	Commercial grade
Turmeric Powder	*Curcuma longa*	Antimicrobial enhancement	Commercial grade
Lavender Oil	*Lavandula angustifolia*	Aroma enhancement and insect repellency	Essential oil

6.3 Equipment and Instruments

The following laboratory equipment and instruments were utilized during the experimental investigation.

Table 3. Laboratory Equipment Used

Equipment	**Purpose**
Precision Digital Balance	Measurement of ingredient quantities
Mechanical Grinder	Pulverization of dried botanical materials
Stainless Steel Sieves	Particle size standardization
Mixing Containers	Homogeneous blending of ingredients
Compression Moulds	Fabrication of BioBlock cubes
Drying Chamber / Ambient Drying	Moisture removal and curing
Airtight Storage Containers	Storage experiments
Laboratory Moisture Analyzer	Moisture determination
Nutritional Analysis Instruments (SV Testing Laboratories Pvt. Ltd.)	Nutritional profiling
Soil Testing Kit	Soil compatibility assessment

6.4 Preparation of Raw Materials

All botanical materials were washed thoroughly using distilled water to remove surface contaminants before being shade-dried under ambient conditions until constant weight was achieved. Drying under indirect sunlight was preferred to minimize degradation of volatile phytochemicals and thermolabile bioactive compounds. The dried materials were subsequently pulverized using a mechanical grinder and sieved to obtain a homogeneous fine powder. Individual powders were stored in airtight moisture-resistant containers until further use.

Fuller's Earth was separately dried and sieved to eliminate coarse particles before incorporation into the formulation.

6.5 Formulation Development

Multiple experimental formulations were prepared to identify the optimum botanical composition capable of providing maximum pest repellency, effective moisture regulation, structural integrity, and prolonged functional life. Various ingredient combinations were evaluated under identical storage conditions before selecting the final formulation.

The optimized BioBlock formulation consisted primarily of neem leaf powder, clove powder, pomegranate peel powder, onion peel powder, and Fuller's Earth, with crop-specific modifications involving turmeric powder, camphor, or lavender oil wherever required.

Table 4. Preliminary Formulation Screening

Formulation	Common Base Ingredients	Variable Ingredient Tested	Evaluation Parameters	Result
F1	Pomegranate peel powder + Clove powder + Fuller's Earth + Onion peel powder	Citrus peels	Pest activity, grain smell, moisture absorption, grain texture	Evaluated
F2	Pomegranate peel powder + Clove powder + Fuller's Earth + Onion peel powder	Garlic peels	Pest activity, grain smell, moisture absorption, grain texture	Evaluated
F3	Pomegranate peel powder + Clove powder + Fuller's Earth + Onion peel powder	Neem leaves	Pest activity, grain smell, moisture absorption, grain texture	**Best overall performance; selected for BioBlock**
F4	Pomegranate peel powder + Clove powder + Fuller's Earth + Onion peel powder	Mint leaves	Pest activity, grain smell, moisture absorption, grain texture	Evaluated

6.6 Manufacturing Procedure

The BioBlock manufacturing process involved sequential processing of botanical ingredients into a compressed biodegradable cube.

The standardized manufacturing procedure consisted of:

1. Collection of botanical raw materials.
2. Cleaning and removal of impurities.
3. Shade drying until constant moisture content.
4. Pulverization and sieving.
5. Homogeneous mixing according to predetermined formulation ratios.
6. Addition of binding matrix.
7. Compression into moulds.
8. Controlled drying and curing.
9. Packaging in biodegradable containers for storage evaluation.

The prepared BioBlocks were subsequently subjected to laboratory validation and field testing.

6.7 Experimental Design

To comprehensively evaluate the performance of BioBlock Repellent, a series of controlled laboratory experiments and field-based investigations were conducted. The study was designed to assess insect repellency, moisture regulation, nutritional preservation, biodegradability, consumer acceptance, and economic feasibility under both controlled and real-world storage conditions.

The experimental work was divided into six independent phases, each addressing a specific performance parameter of the developed formulation.

6.7.1 Phase I: Formulation Optimization

Prior to selecting the final BioBlock composition, multiple botanical formulations containing different combinations of neem leaf powder, clove powder, pomegranate peel powder, onion peel powder, and Fuller's Earth were prepared. Each formulation was evaluated under identical storage conditions for a period of one to two weeks.

The formulations were comparatively assessed based on the following performance indicators:

- Insect repellency
- Moisture absorption capability
- Structural integrity of the compressed cube
- Aroma retention
- Ease of handling
- Physical stability

The formulation exhibiting the most balanced performance across all evaluation criteria was selected as the optimized BioBlock composition for subsequent experimentation.

6.7.2 Phase II: Laboratory Storage Performance Evaluation

A comparative laboratory investigation was conducted to evaluate the storage efficiency of BioBlock against commercially available grain protectants.

Three experimental groups were established:

Table 5. Experimental Groups for Storage Performance Study

Experimental Group	Treatment	Purpose
Group A	BioBlock Repellent	Experimental treatment
Group B	Para Tikdi	Commercial botanical repellent comparison
Group C	Aluminum Phosphide (Alphos)	Chemical fumigant comparison
Group D	Untreated Control	Baseline storage condition

Three commonly stored food grains were selected for evaluation:

- Wheat (*Triticum aestivum*)
- Pulses (Mixed Legumes)
- Pearl Millet (*Pennisetum glaucum*)

Each grain type was stored separately under identical environmental conditions.

6.7.3 Storage Conditions

To ensure uniformity throughout the investigation, all experimental containers were maintained under controlled storage conditions.

Table 6. Controlled Storage Conditions

Parameter	Condition Maintained
Storage Duration	20 Days (Laboratory Validation)
Storage Containers	Airtight Food-Grade Containers
Test Commodities	Wheat, Pulses and Pearl Millet
Experimental Replicates	Three per treatment
Environmental Conditions	Ambient laboratory conditions
Observation Frequency	Periodic throughout the study

6.7.4 Performance Evaluation Parameters

The effectiveness of each treatment was assessed using qualitative observations and laboratory nutritional analysis.

Table 7. Performance Parameters Evaluated

Parameter	**Purpose of Evaluation**
Insect Activity	Assessment of pest infestation
Moisture Content	Evaluation of moisture regulation
Grain Texture	Determination of physical quality
Grain Aroma	Detection of chemical contamination
Nutritional Composition	Preservation of protein, carbohydrates and energy
Structural Integrity	Evaluation of grain damage
Consumer Safety	Presence or absence of toxic residues

6.7.5 Laboratory Nutritional Validation

Nutritional analysis of stored grains was performed by **SV Testing Laboratories Pvt. Ltd., an ISO 9001:2015 Certified Laboratory**, to determine the influence of BioBlock on grain quality during storage. The laboratory assessed protein content, moisture level, carbohydrate content, and total energy value of wheat, pulses, and millet samples stored under different treatment conditions. The analytical results were subsequently compared to evaluate the ability of BioBlock to preserve nutritional quality relative to commercial grain protectants and untreated controls.

6.7.6 Observation and Data Recording

Experimental observations were systematically recorded throughout the study using standardized observation sheets. Both qualitative and quantitative parameters were documented to facilitate comparative analysis between treatments.

Data collected during laboratory investigations included:

- Presence or absence of insect infestation
- Visible grain deterioration
- Moisture variation
- Nutritional profile
- Consumer observations
- Product stability
- Safety characteristics

The recorded observations formed the basis for subsequent statistical interpretation and performance evaluation.

7. Results and Discussion

7.1 Formulation Optimization

Four different botanical formulations were initially prepared to identify the most effective combination for grain protection. Each formulation was evaluated based on pest repellency, moisture regulation, structural stability, and ease of handling. Among all formulations, the combination containing **neem leaf powder, clove powder, pomegranate peel powder, onion peel powder, and Fuller's Earth** demonstrated the best overall performance and was selected as the final BioBlock formulation.

Table 8. Preliminary Formulation Screening

	Common Base Ingredients	Variable Ingredient Tested	Evaluation Parameters	Result
F1	Pomegranate peel powder + Clove powder + Fuller's Earth + Onion peel powder	Citrus peels	Pest activity, grain smell, moisture absorption, grain texture	Evaluated
F2	Pomegranate peel powder + Clove powder + Fuller's Earth + Onion peel powder	Garlic peels	Pest activity, grain smell, moisture absorption, grain texture	Evaluated
F3	Pomegranate peel powder + Clove powder + Fuller's Earth + Onion peel powder	Neem leaves	Pest activity, grain smell, moisture absorption, grain texture	**Best overall performance ; selected for BioBlock**
F4	Pomegranate peel powder + Clove powder + Fuller's Earth + Onion peel powder	Mint leaves	Pest activity, grain smell, moisture absorption, grain texture	Evaluated

7.2 Comparative Storage Performance

BioBlock was compared with Para Tikdi and Aluminum Phosphide (Alphos) under identical storage conditions. The observations revealed that BioBlock effectively prevented insect infestation while maintaining grain freshness without producing any chemical odor. In comparison, Alphos showed effective pest control but imparted a strong chemical smell and posed handling hazards, whereas Para Tikdi exhibited comparatively lower protection against storage pests.

Table 9. Comparative Storage Performance

Parameter	BioBlock	Para Tikdi	Alphos
Pest Control	Excellent	Moderate	Excellent
Grain Freshness	Excellent	Good	Fair
Moisture Control	Excellent	Moderate	Moderate
Chemical Odor	None	Mild	Strong
User Safety	High	Moderate	Low

7.3 Nutritional Analysis

Laboratory analysis demonstrated that BioBlock effectively preserved the nutritional quality of stored grains. Higher protein retention, lower moisture content, and better energy preservation were observed in BioBlock-treated samples compared to chemically treated and untreated grains. Detailed analytical values obtained from laboratory testing are presented in the following sections.

7.4 Nutritional Analysis of Wheat

Laboratory analysis indicated that BioBlock-treated wheat exhibited superior nutritional preservation compared to chemical repellents and untreated storage. The BioBlock formulation effectively maintained protein content while minimizing moisture accumulation, thereby contributing to improved grain quality during storage.

Table 10. Nutritional Analysis of Wheat Samples

Parameter	BioBlock	Chemical Repellent	Untreated Control
Protein (g/100 g)	6.18	5.42	5.67

Moisture (g/100 g)	10.43	11.75	11.03
Carbohydrates (g/100 g)	81.84	81.20	81.18
Energy (kcal/100 g)	352.08	346.48	351.99

BioBlock-treated wheat recorded the **highest protein retention** and **lowest moisture content**, indicating its ability to preserve grain quality more effectively than commercial chemical protectants.

7.5 Nutritional Analysis of Pearl Millet

The nutritional profile of pearl millet demonstrated a similar trend. BioBlock effectively maintained grain composition while restricting moisture absorption during storage.

Table 11. Nutritional Analysis of Pearl Millet Samples

Parameter	**BioBlock**	**Chemical Repellent**	**Untreated Control**
Protein (g/100 g)	11.43	10.12	10.56
Moisture (g/100 g)	10.46	11.78	11.21
Carbohydrates (g/100 g)	76.60	76.44	76.06
Energy (kcal/100 g)	352.12	346.24	351.97

The BioBlock-treated millet samples showed improved protein retention and lower moisture levels compared to the other storage conditions, confirming its effectiveness in maintaining grain quality.

7.6 Nutritional Analysis of Pulses

Among all tested commodities, pulses exhibited the greatest improvement in protein preservation under BioBlock treatment. The formulation effectively minimized moisture uptake while maintaining the nutritional composition of stored pulses.

Table 12. Nutritional Analysis of Pulse Samples

Parameter	**BioBlock**	**Chemical Repellent**	**Untreated Control**
Protein (g/100 g)	19.67	17.23	18.12
Moisture (g/100 g)	10.12	11.76	11.34
Carbohydrates (g/100 g)	68.75	69.44	68.49
Energy (kcal/100 g)	353.68	346.68	351.21

BioBlock preserved the highest protein content and maintained the lowest moisture level, demonstrating its suitability for pulse storage without compromising nutritional quality.

7.7 Overall Nutritional Performance

To compare the overall storage performance across all tested grains, the average nutritional values were calculated.

Table 13. Overall Nutritional Performance of BioBlock

Parameter	**BioBlock**	**Chemical Repellent**	**Untreated Control**
Average Protein (g/100 g)	**12.43**	10.92	11.45
Average Moisture (g/100 g)	**10.33**	11.76	11.19
Average Energy (kcal/100 g)	**352.63**	346.47	351.72

Overall, BioBlock consistently outperformed the commercial repellent and untreated control by maintaining lower moisture levels and better nutritional retention across wheat, pearl millet, and pulses. These findings indicate that the formulation effectively supports long-term grain preservation while minimizing quality deterioration during storage.

7.8 Biodegradation Study

The biodegradability of BioBlock was evaluated by burying the compressed blocks in natural soil and monitoring their degradation over a period of **60 days**. The study aimed to assess the environmental compatibility of the formulation after disposal.

Table 14. Biodegradation Profile of BioBlock

Observation Period	Observation
Day 5	Initial softening of the BioBlock observed
Day 10	Partial degradation and soil integration
Day 30	Significant decomposition of the composite
Day 50–55	Nearly complete degradation
Day 60	Complete biodegradation with no visible residue

The results confirmed that BioBlock decomposed naturally without leaving harmful residues, demonstrating its suitability as an environmentally sustainable grain-protection material.

7.9 Environmental Safety Assessment

To evaluate the environmental impact of BioBlock, soil quality was monitored during the degradation study. Parameters such as soil pH, moisture balance, and visible residues were assessed.

Table 15. Soil Compatibility Assessment

Parameter	Observation
Soil pH	Remained within the neutral range (7.0–7.2)
Moisture Balance	No significant alteration observed
Toxic Residues	Not detected
Environmental Impact	Environmentally safe and biodegradable

The findings indicate that BioBlock integrates safely into the soil without affecting its natural properties or releasing harmful substances..

7.10 Consumer Feedback Survey

A post-distribution survey involving household users and retailers was conducted to evaluate the practical performance of BioBlock under real storage conditions.

Table 16. Consumer Feedback Survey Results

Evaluation Parameter	**Response (%)**
Reduction in pest activity within 24–48 hours	>80%
No skin irritation or health concerns	100%
Rated eco-friendly as Excellent/Good	85%
Preferred BioBlock over conventional repellents	Majority of participants

Survey responses indicated high user satisfaction, particularly regarding product safety, ease of use, and the absence of unpleasant chemical odors.

7.11 Three-Month Performance Assessment

A longitudinal performance assessment involving **50 participants** was conducted to determine the durability and effectiveness of BioBlock during extended storage.

Table 17. Three-Month Performance Evaluation

Duration	**Performance**
Month 1	100% pest-free storage; grains remained fresh and dry
Month 2	Continued effective protection with high user satisfaction
Month 3	Approximately 80% effectiveness; minor pest activity observed in some samples

The field study demonstrated that a single BioBlock remained effective for approximately **60–75 days**, after which a gradual decline in pest-repellent activity was observed.

7.12 Economic Analysis

The production cost of BioBlock was compared with commercially available grain protectants to assess its economic viability.

Table 18. Cost Comparison of Grain Protectants

Product	**Retail Price (₹)**	**Weight (g)**	**Cost per Gram (₹/g)**	**Remarks**
BioBlock	10	20	0.50	Safe, biodegradable, and economical
Alphos	20	10	2.00	Effective but highly toxic
Para Tikdi	95	100	0.95	Moderately effective with higher cost

BioBlock exhibited the **lowest cost per gram** among the evaluated products while providing effective grain protection without compromising safety or environmental sustainability. These findings suggest that BioBlock is a cost-effective alternative for households, retailers, and small-scale farmers.

8. Discussion

The findings of the present study demonstrate that **BioBlock Repellent** is an effective and environmentally sustainable alternative to conventional grain protectants. The optimized formulation successfully combined the insect-repellent properties of neem, clove, pomegranate peel, and onion peel with the moisture-regulating capability of Fuller's Earth, resulting in improved grain preservation under storage conditions.

Comparative evaluation revealed that BioBlock provided pest protection comparable to commercial grain protectants while eliminating the disadvantages associated with synthetic fumigants, such as toxic residues, hazardous handling, and unpleasant chemical odor. The laboratory results further indicated superior moisture regulation and nutritional preservation in BioBlock-treated grains, suggesting that the botanical formulation effectively maintained grain quality during storage.

The biodegradation study confirmed that BioBlock decomposed naturally within approximately **60 days** without adversely affecting soil quality or leaving harmful residues. This characteristic makes the product environmentally compatible and supports its application as a sustainable grain storage solution.

Consumer feedback further validated the practical applicability of BioBlock, with participants reporting high levels of satisfaction regarding product safety, ease of use, and effectiveness. The observed functional lifespan of **60–75 days** indicates that BioBlock can provide reliable protection during routine household and retail grain storage.

Overall, the findings are consistent with previous studies highlighting the insecticidal properties of botanical materials such as neem and clove while extending their application through a biodegradable slow-release composite. The incorporation of agricultural waste materials further enhances the environmental and economic value of the developed formulation.

9. Novelty of the Study

The present study introduces a multifunctional biodegradable grain protectant developed from agricultural and household organic waste. Unlike conventional storage protectants, BioBlock integrates insect repellency, moisture regulation, nutritional preservation, and environmental sustainability within a single biodegradable formulation.

The major innovations of the study include:

- Development of a biodegradable grain-protection cube utilizing kitchen and agricultural waste.
- Integration of multiple botanical ingredients for synergistic pest control.
- Simultaneous moisture regulation and grain preservation.
- Elimination of toxic chemical residues associated with synthetic fumigants.
- Validation through laboratory testing, biodegradation assessment, and field performance evaluation.
- Promotion of circular economy principles through waste valorization.

Table 19. Novel Features of BioBlock

Parameter	**Conventional Repellents**	**BioBlock Repellent**
Natural Ingredients	✗	✓
Biodegradable	✗	✓
Toxic Residues	Present	Absent
Moisture Regulation	Limited	Effective
Nutritional Preservation	Moderate	High
Kitchen Waste Utilization	✗	✓
Environmental Safety	Low	High

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10. Limitations of the Study

Although the findings demonstrate the effectiveness of BioBlock, certain limitations should be acknowledged. The experimental validation was conducted under controlled laboratory conditions and limited field environments. Climatic variations, storage duration exceeding three months, and large-scale warehouse conditions were beyond the scope of the present investigation. In addition, the study primarily focused on wheat, pulses, and pearl millet; therefore, further validation across a wider range of stored commodities is recommended.

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11. Future Scope

Future research may focus on improving the formulation by incorporating additional botanical extracts to enhance the duration of protection. Large-scale field trials involving different climatic regions and storage infrastructures may further establish the commercial applicability of the product. Development of crop-specific formulations, automated manufacturing techniques, and eco-friendly commercial packaging may facilitate industrial-scale production. Furthermore, detailed investigations on long-term storage stability and international regulatory compliance would support commercialization and wider adoption.

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12. Conclusion

The present study successfully developed **BioBlock Repellent**, a biodegradable botanical grain protectant formulated from agricultural and household organic waste. The integration of neem, clove, pomegranate peel, onion peel, and Fuller's Earth produced an effective slow-release composite capable of protecting stored grains while preserving their nutritional quality.

Laboratory validation demonstrated improved moisture regulation, higher protein retention, and effective pest control compared with conventional storage methods. Soil degradation studies confirmed complete biodegradability without adverse environmental effects, while field evaluations established an effective functional lifespan of approximately **60–75 days** with high consumer acceptance.

In addition to providing a safer alternative to synthetic fumigants, BioBlock promotes sustainable waste management by converting discarded organic materials into a value-added agricultural product. The technology therefore represents a practical, economical, and environmentally responsible solution for post-harvest grain protection and contributes toward sustainable agriculture, food security, and circular bioeconomy.

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