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Botanical-Based Granular Insecticides for Sustainable Management of *Sitophilus oryzae* in Stored Rice under Seasonal Conditions

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ABSTRACT

The rice weevil, *Sitophilus oryzae* (L.), is a predominant stored grain pest responsible for substantial quantitative and qualitative losses in stored cereals. This study investigated the efficacy of botanical-based granular bioinsecticides against *S. oryzae* in stored rice. Granules formulated with diatomaceous earth, powdered botanicals (neem, clove, cinnamon, nutmeg), and eucalyptus oil were evaluated at 0.34g, 0.60g, and 1.05g per 20g of rice under both winter and summer conditions. Phytochemical profiling of the granules was conducted using GC-MS and FTIR analyses confirmed the presence of key bioactive compounds, including eugenol, azadirachtin, cinnamaldehyde, and 1,8-cineole. Laboratory bioassays were conducted to evaluate the efficacy of 3 botanical-based granule biopesticides (0.34g, 0.60g, and 1.05g per 20g rice) under controlled winter and summer environmental conditions. The highest dosage (1.05g) resulted in a significant increase in mortality rates (100%) and a marked reduction in grain weight loss and damage indices compared to controls ($p < 0.05$). In addition, the treatment effectively inhibited F_1 progeny emergence during summer and provided maximum grain protection of 100.00% and 98.28% under summer and winter storage conditions respectively. Seasonal variation indicated enhanced efficacy under higher temperature regimes. These findings substantiate the potential of plant-derived granular formulations, combined with diatomaceous earth, as sustainable and environmentally benign alternatives for managing *S. oryzae* infestations in stored rice grains.

Keywords: Bioinsecticides, neem, clove, cinnamon, nutmeg, grain protection, seasonal variation.

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INTRODUCTION

Modern agriculture has increased food production, but stored grains remain vulnerable to insect infestations, threatening food security (Mohammad, Haniffa, & Sujarajiini, 2023; Mohammad, Haniffa, Shakya, Naik, & Sivaranjan, 2024). Rice weevil (*Sitophilus oryzae L.*) poses a significant threat to stored grains, leading to substantial economic losses globally. Their management requires innovative, sustainable approaches, as highlighted by recent studies. Deep-freezing methods, particularly at -196°C, have effectively checked rice weevils from packaged grains (Ma et al., 2024). Similarly, spinetoram has emerged as a promising alternative to conventional insecticides due to its high efficacy and reduced progeny production (Rajarushi, Nebapure, Biswas, Rajna, & Subramanian, 2024). The role of grain properties, such as protein and fat content, in pest susceptibility has been extensively studied, revealing opportunities to develop pest-resistant grain cultivars (Abedi, Razmjou, Dastjerdi, & Ebadollahi, 2024; Kosewska, Nietupski, Koronkiewicz, & Przemieniecki, 2024). Integrating these strategies within an IPM framework, complemented by advancements like monoterpene-enhanced insecticides and improved monitoring techniques, holds promise for effective and sustainable control of *S. oryzae* in stored grains (Abdelgaleil, Gad, Al-Anany, & Atta, 2024a; Zhang, Zhou, Miao, Du, & Wang, 2024).

Plant-based bioactive compounds, including neem, moringa, and clove oil, offer eco-friendly alternatives with significant insecticidal and deterrent effects, providing pest control options (Nta, Agbo, Etim, Bassey, & Imalele, 2024; El-Talpanty, Abuarab, Abouelatta, & Elmadawy, 2024). Recent research has focused on plant-derived powders, essential oils, and diatomaceous earth as potential bio-insecticides for sustainable pest management (Ileke & Olaposi, 2024; Ali et al., 2024; Srivastava & Awasthi, 2024a). Several studies have evaluated the efficacy of botanical powders against key storage pests. Research on clove basil (*Ocimum gratissimum)* and sweet basil (*O. basilicum)* powders has demonstrated their insecticidal potential against *Tribolium castaneum* in stored wheat, showing that mortality rates increased with higher doses and more prolonged exposure, with *O. basilicum* proving most toxic (Ileke & Olaposi, 2024). Testing six botanical powders against the rice moth (*Corcyra cephalonica*) revealed that neem (*Azadirachta indica*) seed powder exhibited the highest larval mortality and repellency (Murugesan et al., 2024).

In contrast, nicotine powder reduced fecundity and oviposition (Ali et al. 2024). Similarly, studies on coffee senna (*Asparagus racemosus)* and shatavari (*Cassia occidentalis)* powders for controlling *S. oryzae* in stored rice found that *C. occidentalis* displayed the highest efficacy (Srivastava & Awasthi, 2024b). Essential oils have also demonstrated significant potential as biopesticides. Studies combining Spinosad with monoterpenes against *S. oryzae* achieved complete mortality with certain combinations (Abdelgaleil, Gad, Al-Anany, & Atta, 2024b). The superior toxicity of nano-emulsified anise oil has been highlighted, reducing *S. oryzae* emergence by 94.64% and protecting 84.5% of wheat grains from *T. castaneum* (Draz, Tabikha, Eldosouky, Darwish, & Abdelnasser, 2024). Further evaluations of *Callistemon lanceolatus* leaf oil against three storage pests identified strong repellent, contact, and fumigation toxicity properties, particularly against *Callosobruchus maculatus* (Ankitha et al., 2024).

Research on essential oils and their combinations has shown promising results. Assessments of *Ocimum basilicum* and *Citrus reticulata* essential oils alongside lambda-cyhalothrin against *S. oryzae* and *Rhyzopertha dominica* analyzed their impact on F1 progeny and grain quality. LC_{50} values decreased over time, with petitgrain mandarin (104.45 mg/kg) showing higher toxicity than basil oil (108.08 mg/kg) against *S. oryzae*. Basil oil reduced *S. oryzae* progeny by 90.72% and *R. dominica* by 82.15%, while lambda-cyhalothrin showed 63.3% and 66.07% reductions, respectively (Abo Arab, El-Tawelah, Abouelatta, & Hamza, 2022). Investigations into nano-emulsions of *Carlina acaulis, Mentha longifolia*, and *Hazomalania voyronii* found that *C. acaulis* nano-emulsion was most effective on barley, achieving 94.4% mortality (Kavallieratos et al., 2023). Diatomaceous earth (DE) has been widely studied for its insecticidal and repellent properties. Evaluations of Sayan® DE against *S. oryzae*, *Oryzaephilus surinamensis*, and *T. castaneum* observed dose- and time-dependent mortality, with *O. surinamensis* being the most susceptible (Amiri-Besheli, Doustdtar, & Raeis, 2017). Similarly, studies on Detech® DE applied to different wooden surfaces against *S. oryzae* found that higher doses and longer exposure times led to complete mortality on concrete surfaces (Ertürk, Atay, Toprak, & Alkan, 2020). Another promising area of research is the insecticidal effect of Juniperus powders. Investigations into *Juniperus phoenicea* and *J. oxycedrus* powders, alone and in combination, against *T. castaneum* and *R. dominica* found that *J. phoenicea* was the most effective, with binary combinations enhancing toxicity and significantly reducing LD50 values (Naimi, Bouamama, & M'hamed, 2025). In the present study, formulated granules were developed and evaluated for their efficacy against the major stored grain pest, *S. oryzae*, with across different seasonal conditions.

MATERIALS AND METHODS

Collection and preparation of plant powder

Fresh samples of nutmeg (*Myristica fragrans*), *clove (Syzygium aromaticum), cinnamon (Cinnamomum verum), neem* (*Azadirachta indica),* and eucalyptus essential oil (*Eucalyptus globulus)* were procured from the local market, carefully labelled, and placed in manila bags for transportation to the experimental site within 24h. The *E. globulus* essential oil was procured from the Nilgiris Eucalyptus Oil and Essential Oils Distillery (TNEOEOD), Ooty, Tamil Nadu, India. The plant materials were shade-dried at ambient temperatures (18-28°C) for 14 days, followed by oven drying at 35°C for 48h, as described by Wambua et al. (2011). The dried samples were ground into fine powders using an electric laboratory hammer mill. The resulting powders were stored in airtight glass jars in a cool, dark location to prevent exposure to sunlight and to prevent quality loss.

Formulation of granules

One hundred grams of granules were formulated with the composition of nutmeg (10 g), clove (30 g), cinnamon (15 g), neem (15 g), diatomaceous earth (25 g) and eucalyptus essential oil (5 ml). Two grams of starch was added to 50 ml of distilled water and heated with continued stirring until a thick consistency formed and coded. The powders were mixed with starch and the mixture was made up to uniform tiny granules. The granules were dried for two days and used for bioassay studies against *S. oryzae.*

Characterization of granules

Sample preparation for GC-MS Analysis

The formulated plant granules were air-dried at room temperature and ground into a fine powder using a sterile mortar and pestle. Approximately two grams of granule powder was extracted with 20 mL of HPLC-grade methanol in a conical flask. The mixture was sonicated at 40 °C for 30 min to facilitate the extraction of volatile and semi-volatile phytoconstituents following the method described by Adams (2007) with slight modifications. The extract was filtered through Whatman No. 1 filter paper and concentrated under reduced pressure using a rotary evaporator at 40 °C. The filtered extract was stored in amber glass vials at 4 °C until analysis.

Gas Chromatography Mass Spectrometry (GCMS) analysis

GC-MS analysis was carried out using an Agilent DB5MS fused silica capillary column (30m / 0.25mm internal dia / 0.25-micron film thickness) in conjunction with an Agilent GC 7890A / MS5975C apparatus. A volume of solvent extract weighing one liter was injected into the gas chromatograph (GC) oven. The temperature was first raised from 60℃ to 120℃ at a rate of 10℃ /min, then raised at a rate of 3℃/ min up to 175℃, raised at a rate of 5℃/ min, held for 5 min, offering a total runtime of 55.583 min. As a carrier gas, helium was employed at a steady flow rate of 1.0 mL/ min. At an electron energy of 70 eV and an interface temperature of 280℃, the mass spectrometer was run in full scan mode. The MS quadruple temperature was set at 150℃, while the MS source temperature was set at 230℃. The scan range included m/z 30 to 550. Identification of compounds was performed by comparing the obtained mass spectra with the NIST08.L library database (Al-Owaisi, Al Hadiwi, & Khan, 2014).

Fourier Transform Infrared Spectroscopy (FTIR) analysis

FTIR analysis was carried out using the potassium bromide (KBr) pellet technique described by Stuart (2004). FTIR analysis was conducted to identify functional groups present in the granule extract. The dried sample was finely ground and mixed with potassium bromide (KBr) in a 1:100 ratio to prepare a pellet using a hydraulic press under vacuum. The FTIR spectra were recorded using a PerkinElmer Spectrum Two FTIR spectrometer in the range of 4000-400 cm^{-1} with a resolution of 4 cm^{-1} and 32 scans per sample. The functional groups were identified based on their characteristic absorption peaks, and interpretations were made by referring to standard FTIR peak correlation charts and existing literature (Jain, Soni, Jain, & Bhawsar, 2016).

Rearing of *S. oryzae*

S. oryzae was reared on rice grains in glass jars under controlled conditions of 27 ± 2°C and 70 ± 5% relative humidity. The culture was maintained for multiple generations to ensure a stable population for bioassay studies (Aslam et al. 2002).

Bioassay studies

Adult mortality of *S. oryzae* in summer and winter seasons

Twenty grams of disinfected rice were measured and placed in plastic containers (250 mL). Then, rice was treated with formulated granules at different concentrations of 0.34, 0.60, and 1.05g for each formulation (in three duplicates). Ten mature adult *S. oryzae* (less than 4 days old male and female in the ratio of 1:1) were introduced to each container of the treated rice grains. Only 20 g of rice and five copulating pairs of mature *S. oryzae* were used in the control experiment. The same setup was maintained for both summer and winter seasons. The mortality of insects was observed daily for 7 consecutive days. Data on the percentage of adult mortality were corrected using the formula.

$$Percentage\ mortality\ of\ insects = \frac{Dead\ insects}{Introduced\ insects} \times 100 \qquad (1)$$

Weight loss of rice in summer and winter seasons

To measure the weight loss of the rice, the control and treatment groups were sieved to get rid of all the dust and insects. A digital balance was used to determine the weight of the leftover grains. The following formula was used to determine the percentage of weight loss (Harris & Linblad, 1978).

$$Percentage\ of\ weight\ loss = \frac{Initial\ weight\ of\ grains\ (g) \times Final\ weight\ of\ grains\ after\ storage\ (g)}{Initial\ weight\ of\ grains\ (g)} \qquad (2)$$

F_1 Progeny Emergence

The effect of the treatments on progeny development of *S. oryzae* was assessed by recording F_1 adult emergence following the procedure described by Awadallah et al. (2024). Twenty unsexed adults (7-14 days old) were introduced into containers containing treated rice grains and allowed to oviposit for 7 days. After the oviposition period, all parent adults were removed. The experimental units were maintained under laboratory conditions (27 ± 2 °C and 65 ± 5% RH). Emergence of F_1 adults was monitored daily beginning 30-35 days after infestation and continued until no further adults emerged. The total number of newly emerged adults was recorded as the F_1 progeny. The progeny emergence of *S.oryzae* was calculated as using the formula:

$$F_1\ \textit{Progeny Emergence (Nos.)} = \sum \textit{Number of newly emerged adults} \qquad (3)$$

Grain Protection

The protective effect of the treatments against grain damage was determined at the end of the storage period based on grain weight loss (Arthur & Morrison, 2020). Percentage protection was calculated using grain weight loss according to the method commonly employed in stored-product insect studies:

$$\textit{Protection (\%)} = \frac{WL_c - WL_t}{WL_c} \times 100 \qquad (4)$$

WLc = Grain weight loss (%) in untreated control

WLt = Grain weight loss (%) in treated grain

Statistical analysis

Results were expressed as the mean±sd (SD). Data were analyzed using one-way ANOVA, and the mean values were compared using the Duncan multiple range test using the software program SPSS version 16 for Windows. Differences were considered statistically significant ($P<0.05$).

RESULTS

GCMS analysis

The chemical composition and active components of the formulated granules were analysed using Gas Chromatography and Mass Spectrometry (GC/MS). The GC/MS analysis of granules revealed chemical contents, including their molecular weight, retention duration, and peak area (Table 1). The GC/MS study of granules found 50 components in the aqueous extract. The analysis shows six prominent peaks as Phenol,2,4-bis(1,1-dimethylethyl) ($C_{17}H_{30}OSi$) with the retention time of 12.230 (5.72%), 1-Methoxy-3-(2-hydroxyethyl)nonane ($C_{12}H_{26}O_2$) with the retention time of 9.697 (13.08%), 1-Nonadecene ($C_{19}H_{38}$) with the retention time of 13.297 (3.20%), 2,6,10,14,18,22-Tetracosahexaene,2,6,10,15,19,23-hexamethyl-,(all-E) ($C_{24}H_{38}$) with the retention time of 17.941 (16.21%), Eicosane ($C_{20}H_{42}$) with the retention time of 19.975 (7.62%), Eicosane ($C_{20}H_{42}$) with the retention time of 22.140 (7.60%). It has six prominent peaks with other small peaks indicating the presence of major compounds (Fig. 1). The compounds found in this result were considered as the major bio-active compounds that were helpful for the insecticidal activity.

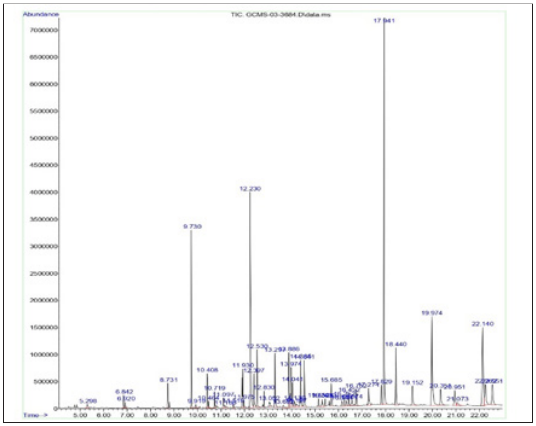

Figure 1. GC-MS chromatographic profile of plant-based granules.

Table 1. Chemical compound identified in chronological order using GCMS analysis of *Eucalyptus globulus* essential oil.

S.NO.	Compound name	Retention time (min)	Area%
	9-Octadecene, (E)-	8.731	0.81
	Phenol, 2,4-bis(1,1-dimethylethyl)	9.730	5.71
	9-Eicosene, (E)-	10.408	1.42
	1-Nonadecene	11.930	2.76
	1-Methoxy-3-(2-hydroxyethyl) nonane	12.230	13.08
	9-Octadecyne	12.530	2.36
	Trifluoroacetoxy hexadecane	13.297	3.20
	Phytol	14.041	0.93
	9,12,15-Octadecatrienoic acid,	14.385	2.25
	1-Docosene	15.685	1.39
	Nonadecyl pentafluoropropionate	16.752	1.18
	Octacosane	17.829	1.18
	2,6,10,14,18,22-Tetracosahexaene,	17.941	16.21
	Tridecane, 7-hexyl-	18.440	2.96
	Hexadecane	19.151	1.60
	Heptadecane, 9-octyl-	19.974	7.62
	dl-.alpha.-Tocopherol	20.351	1.42
	Docosane, 5-butyl-	20.951	1.42
	Silane, trimethyl[5-methyl-2-(1-methylethyl)phenoxy]-	21.073	0.46
	Stigmasta-7,25-dien-3-ol,	22.551	2.23

FT-IR spectroscopy analysis

The FT-IR spectrum was used to identify the functional group of the active components based on the peak in the infrared radiation region (Table 2). IR analysis of the whole formulated granules revealed that the presence of different functional groups ranging from aliphatic primary amine (3323.71 cm^{-1}), CH- structure alkaline (2941.88 cm^{-1}), medium CH-aldehyde (2831.95cm^{-1}), medium C=N amine (1645.45 cm^{-1}), strong sketching S=O sulphide (1409.71 cm^{-1}), strong CO-secondary alcohol. Therefore, the FT-IR analysis on formulated granules displayed novel phytochemical markers as a useful analytical tool to check out not only the quality of the powder but also to identify the medicinally important plant (Fig. 2).

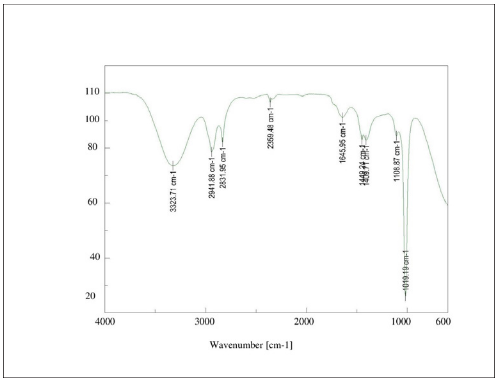

Figure 2. FTIR analysis of functional groups in plant-based granules.

Table 2. FTIR Spectroscopic analysis of plant-based granules.

S.NO	Group	Stretching Frequency (cm^{-1})
1.	Aliphatic primary amine	3323.71
2.	CH- structure alkaline	2941.88
3.	Medium CH- aldehyde	2831.95
4.	Medium C=N amine	1645.95
5.	Strong sketching S=O sulphide	1409.71
6.	Strong CO - secondary alcohol	1108.87

Adult mortality of *S. oryzae* in summer and winter seasons

The efficacy of different concentrations of granule formulations was evaluated based on adult mortality of *S. oryzae* and weight loss of stored grains during both summer 35℃ (April and May) and winter 17℃ (December and January) seasons. The results demonstrated a significant ($P<0.05$) dose-dependent increase in adult mortality and a corresponding decrease in grain weight loss across treatments. In the summer season, the highest adult mortality (100.00 %) was recorded at the 1.05 g concentration, which was significantly higher than the mortality observed at 0.60 g (85.00 %) and 0.34 g (63.33 %). The control group exhibited the lowest mortality (35.00 %). Similarly, in the winter season, adult mortality followed a comparable trend, with 1.05 g achieving the highest mortality (88.33%), followed by 0.60g (70.00%) and 0.34 g (53.33%), while the control remained at 34.00 % (Table 3).

Weight loss of grains in summer and winter seasons

Grain weight loss was significantly reduced with increasing granule concentrations. During the summer, the highest weight loss was maximum in the control group (28.73%), while the 0.34 g and 0.60 g recorded minimum weight loss of 8.33% and 0.83%, respectively. The 1.05 g treatment showed complete protection with no measurable weight loss (0.00 %). In the winter, weight loss followed a similar trend, with the control recording the highest loss (29.10 %), and the 1.05 g treatment again providing almost complete protection (0.50 %). The statistical analysis revealed that all observed differences were significant at $P<0.05$ (Table 3).

Table 3. Mean ± SE for percentage mortality of adult *S. oryzae* and weight loss of grains at different concentrations.

Concentration of granules	Adult mortality (%) Summer	Adult mortality (%) winter	Weight loss (%) summer	Weight loss (%) winter
Control	35.00 ± 2.50^{d}	26.66 ± 3.33^{d}	28.73 ± 1.12^{a}	29.10 ± 0.66^{a}
0.34g	63.33 ± 3.00^{c}	53.33 ± 2.89^{c}	8.33 ± 0.35^{b}	16.66 ± 0.63^{ab}
0.60g	85.00 ± 2.89^{b}	70.00 ± 3.00^{b}	0.83 ± 0.44^{c}	4.83 ± 0.32^{c}
1.05g	100.00 ± 0.00^{a}	88.33 ± 2.50^{a}	0.00 ± 0.00^{cd}	0.50 ± 0.28^{cd}
Grand mean	70.42	61.42	9.47	12.77
SED	6.90	6.75	3.50	3.36

Means with the same letter in each column not significantly different; SED - Standard Error Deviation; ** - Significant at $p< 0.05$.

F1 Progeny Emergence of *S. oryzae* in summer and winter seasons

F_1 progeny emergence of *S. oryzae* was significantly reduced with increasing granule concentrations. During the summer, the highest progeny emergence was observed in the control group (87.00nos adults), while the 0.34 g and 0.60 g treatments recorded reduced progeny emergence of 12.33nos and 5.66nos adults, respectively. The 1.05 g treatment completely suppressed progeny emergence, with no adult emergence recorded (0.00). During the winter, a similar trend was observed, with the control recording the highest progeny emergence (87.00nos), whereas the 0.34 g, 0.60 g and 1.05 g treatments recorded 25.00nos, 14.00nos and 5.33nos adults, respectively. Compared to winter, summer storage with the formulated granules showed more effectiveness against rice weevil, *S.oryzae*. The statistical analysis revealed that all observed differences were significant at P<0.05 (Table 4).

Table 4. Mean ± SE of F_1 progeny emergence (nos.) and grain protection (%) in rice treated with different concentrations of plant granules against *S. oryzae*.

Concentration of granules	F1 progeny Emergence Summer	F1 progeny Emergence Winter	Grain Protection (%) Summer	Grain Protection (%) Winter
Control	87.00^{a}	87.00^{a}	-	-
0.34g	12.33^{b}	25.00^{b}	70.99 ± 1.73^{a}	42.72 ± 3.10^{c}
0.60g	5.66^{c}	14.00^{c}	97.09 ± 2.17^{b}	83.38 ± 1.59^{b}
1.05g	0.00^{d}	5.33^{d}	100.00 ± 0.00^{a}	98.28 ± 1.40^{a}
Grand mean	9.42	12.42	89.47	70.77
SED	2.90	2.75	4.50	4.36

Means with the same letter in each column not significantly different; SED - Standard Error Deviation; ** - Significant at p< 0.05.

Grain Protection Against *S. oryzae* in summer and winter seasons

Grain protection increased significantly with increasing granule concentrations. During the summer, the lowest protection was recorded at 0.34 g (70.99%), while the 0.60 g treatment provided 97.09% protection. The highest concentration (1.05 g) afforded complete grain protection (100.00%). During the winter, grain protection was 42.72%, 83.38%, and 98.28% protection recorded at 0.34 g, 0.60 g, and 1.05 g, respectively. The maximum protection was achieved at the highest concentration (1.05g), indicating the effectiveness of the granule formulation in preventing grain damage caused by *S. oryzae* under both storage conditions. The statistical analysis revealed that all observed differences were significant at P<0.05 (Table 4).

DISCUSSION

The different plant powder and diatomaceous earth combinations had greater mortality effects during summer and winter seasons, which prevented grain damage by suppression of *S. oryzae* population (Fig. 3). Our findings are consistent with a growing body of literature that shows a synergistic effect of nutmeg (*M. fragrans*), *clove (S. aromaticum), cinnamon (C. verum), neem* (*A. indica),* and eucalyptus essential oil (*E. globulus)* as insecticides for stored grain pest management. Bandara & Senevirathne (2023) found that clove stem oil showed superior insecticidal activity against *S. oryzae*, with 100% repellency and 96.67% mortality at 100 µL, and the lowest LD_{50} value of 28.06 µL/L after 5 days. The valorization of clove waste as an effective, sustainable alternative to synthetic insecticides in stored grain protection. Similarly, Zeng, Lao, Cen, & Liang (2010) demonstrated that GC-MS analysis identified

2-methoxy-4-(2-propenyl)-phenol as the dominant compound, accounting for 83% of the oil. Toxicity tests revealed comparable mortality between this compound and whole clove oil, indicating it as the primary active agent. In another study, Mahmoud, Azab, & Sleem (2023) reported that the insecticidal and repellent efficacy of *C. verum* powder and extract against *C. ferrugineus* and *S. granarius* revealed species-specific responses, most susceptible to the extract and most affected by the powder. LC_{50} values indicated strong toxicity within 24h, and repellency reached up to 100% with powder treatments. Sharma, Hariprasad, & Satya (2024) focused on formulating a eucalyptus essential oil-based nanoemulsion (EO-NE) to control *Callosobruchus maculatus*, a major legume pest. The EO-NE demonstrated excellent kinetic stability, nanoscale droplet size (17.16 nm), and enhanced physicochemical properties, including increased adhesiveness and reduced contact angle. These results suggest EO-NE as a promising green alternative to synthetic pesticides for protecting stored legumes. Furthermore, the study by Nukenine, Tofel, & Adler (2011) evaluated the efficacy of Neem Azal, neem seed oil (NSO), neem seed powder (NSP), and *Plectranthus glandulosus* powder against Maize weevil (*Sitophilus zeamais)* in stored maize. Neem Azal and NSO achieved the highest mortality rates and significantly reduced F_1 progeny emergence and grain damage. Neem Azal demonstrated superior grain protection and preservation of germination quality compared to local botanicals. These findings support the potential of Neem Azal and NSO in integrated pest management strategies for stored grain protection. Similarly, Facknath (2006) investigated the combined effect of neem products and grain movement on pest control in stored beans and rice. Neem treatments, including dried whole neem leaves, neem leaf powder, and neem seed kernel oil, were used in conjunction with gentle grain tumbling to reduce pest populations and disrupt their growth. The combined approach proved more effective than using neem or tumbling alone against pests like *Acanthoscelides obtectus*, *S. oryzae*, *O. surinamensis*, and *Cryptolestes ferrugineus*. This study highlights this method as a simple, affordable solution for small-scale grain storage, particularly for resource-poor farmers. The biological activity of nutmeg seed powder and oil against *C. maculatus*, the cowpea storage bruchid, showed significant contact toxicity, achieving 85% mortality at the 2% dosage after 7 days. Both nutmeg oil and powder inhibited oviposition and reduced adult emergence, with oil completely preventing adult emergence. Nutmeg oil also protected seeds from damage over 12 weeks, slightly reducing germination at higher dosages (Adedire, 2002). The long-term effectiveness of the diatomaceous earth product SilicoSec® against major stored grain pests in wheat over 12 months. At 1000 mg/kg, SilicoSec® significantly suppressed *Sitophilus granarius*, *Rhyzopertha dominica*, and *Tribolium confusum*, achieving over 95% control. The 2000 mg/kg dose further minimized pest survival, confirming the strong residual efficacy of DE (Mortazavi et al., 2025). In the present study, the application of a combination of these plant materials with diatomaceous earth acted as a high contact toxicity against *S. oryzae*, entering the insect cuticle and penetrating the insect's body, particularly in the presence of different volatile compounds leading to enhanced insect mortality.

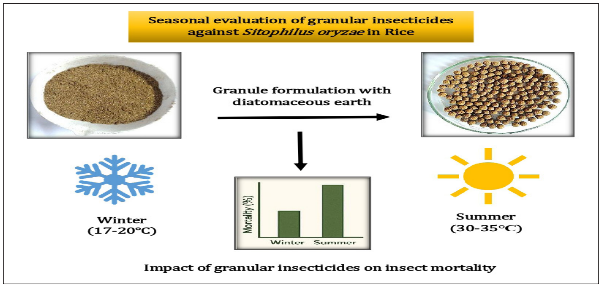

Figure 3. Flowchart illustrating the formulation of ecofriendly plant-based granules with diatomaceous earth, their application on stored grains, and the comparative seasonal evaluation of insect mortality during winter (17-20°C) and summer (30-35°C).

The GC-MS chromatogram of the extract revealed the presence of multiple peaks, indicating a diverse array of volatile phytochemicals. Notably, major peaks were observed at retention times 9.730, 12.230, and 17.941 min, corresponding to significant bioactive compounds. These constituents include hydrocarbons, esters, fatty acids, and phenolic derivatives, are known for their antimicrobial, antioxidant, and insecticidal properties (Ali et al., 2021). The presence of such phytoconstituents supports the therapeutic and pesticidal potential of the extract. Similar studies have shown that plant-derived volatiles detected through GC-MS contribute to natural defense mechanisms against pests and pathogens (Chhikara et al., 2022; Alghamdi et al., 2023). The FTIR spectrum of the extract revealed several prominent absorption bands, indicating the presence of various functional groups associated with bioactive compounds. A broad and intense peak observed at 3323.71 cm^{-1} corresponds to the O-H stretching vibration, suggesting the presence of hydroxyl groups, commonly found in alcohols and phenolic compounds (Sundar, Karthikeyan, & Sivaraj, 2016). The bands at 2941.88 cm^{-1} and 2831.95 cm^{-1} are attributed to C-H stretching vibrations of aliphatic $-CH_3$ and $-CH_2$ groups, indicating the presence of alkanes (Prabakaran, Ashokkumar, & Ravi, 2020). A peak at 1645.95 cm^{-1} corresponds to C=C or C=O stretching, which may indicate aromatic rings or carbonyl groups present in flavonoids and terpenoids (Kumar, Rajkapoor, Perumal, & Kavitha, 2014). Moreover, the absorption bands at 1409.34 cm^{-1} and 1108.87 cm^{-1} suggest the presence of C-N stretching and C-O stretching vibrations, respectively, indicating the presence of amines and esters.

The comparative analysis of the present study revealed a consistently lower mortality of *S. oryzae* in winter than in summer across all treatment concentrations. This variation can be attributed to the insect's poikilothermic nature, where physiological and metabolic functions are highly dependent on ambient temperature. During winter, reduced temperatures slow down the weevil's metabolic rate, resulting in decreased mobility, feeding, and respiration. Consequently, the insects have limited interaction with treated granules, leading to lower exposure and reduced mortality. In addition to the above, the efficacy of biogenic and plant-based formulations may be temperature- and humidity-dependent, with optimal performance under warmer and more humid conditions. In winter, lower humidity and cooler temperatures likely hinder the release, dispersion, and absorption of active ingredients, thereby diminishing their effectiveness. These findings highlight the importance of seasonal timing in treatment applications, suggesting that early post-harvest or summer applications may yield better control outcomes due to increased pest activity and enhanced efficacy of treatment agents. Similar findings were proposed by Rajan et al. (2018) who observed the seasonal flight dynamics of *T. castaneum*, *R. dominica*, and *S. oryzae* across different habitats and climatic zones in India using pheromone traps. Results indicated higher beetle abundance near bulk grain storages, particularly for *T. castaneum*, which showed peak activity during post-monsoon in the south. Regional and species-specific variations were observed with temperature significantly. Influencing trap catches and the importance of climate and habitat in shaping pest dispersal patterns were studied with implications for region-specific pest management strategies. Another study by Holloway, Daglish, & Mayer (2020) who utilized pheromone traps to monitor the flight activity of *R. dominica* and *T. castaneum.* Results showed that both species exhibited strong seasonal patterns, with flight activity ceasing during winter months (June-August). The study also found a correlation between maximum daily temperatures and trap catches, suggesting temperature thresholds for flight activity at 14.5°C for *R. dominica* and 15.6°C for *T. castaneum.* Additionally, Jipsa, Midhun, P. & Sethulakshmi (2023) surveyed stored grain pests across two seasons in Thrissur District, Kerala. Nine species were recorded, with *S. oryzae* and *T. castaneum* being the most abundant during both monsoon and post-monsoon seasons. This research highlights the influence of breeding seasons on pest abundance and provides insights into species diversity in the region

CONCLUSIONS

The present study demonstrates that integrating plant-based powders with diatomaceous earth provides an effective and eco-friendly strategy for managing *S. oryzae* in stored grains. The GC-MS and FTIR analyses revealed the presence of potent bioactive compounds with insecticidal properties, validating their efficacy. Seasonal variations significantly influenced pest mortality, highlighting the importance of optimizing treatment timing for maximum control. These findings reinforce the potential of using locally available botanical resources in combination with inert dusts as a sustainable alternative to chemical insecticides especially during summer for best activity. This approach offers a promising component for integrated pest management (IPM) in post-harvest grain storage systems.

Authorship contribution

MK Writing - original draft, Visualization, Validation, Investigation, Formal analysis. GM: Writing - review & editing, Supervision, Project administration

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Declaration of competing interest

The authors declare that they have no known competing interests that could have appeared to influence the work reported in this paper.

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