A SOLAR-POWERED ULTRASONIC DEVICE FOR SUSTAINABLE CONTROL OF STORED-PRODUCT INSECTS: DESIGN AND LABORATORY EVALUATION

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Abstract. This study aimed to evaluate the effectiveness of a solar-powered ultrasonic device for managing insect pests of stored agricultural products. The fabricated device emits ultrasound in a three-dimensional (3D) configuration and is powered by solar energy. Its signal generation is based on a Phase-Locked Loop (PLL) integrated circuit (LM567), allowing precise control of frequency output. Six common stored-product insect species were exposed to ultrasound frequencies of 40, 80, and 104 kHz under laboratory conditions, with varying exposure durations (5, 10, and 15 min) and directional configurations (one, two, or three speakers). Mortality rates were significantly affected by frequency ($F = 21.67$, $p < 0.001$), exposure time ($F = 18.24$, $p < 0.001$), and speaker configuration ($F = 15.89$, $p < 0.01$). The highest mortality—reaching 100% in five of the six tested species—was achieved at 104 kHz using a three-speaker setup for 15 min. These findings demonstrate the strong potential of ultrasound as a non-chemical, energy-efficient pest control method. This device offers a promising and scalable alternative for chemical-free insect management in postharvest grain storage systems, particularly in resource-limited or off-grid environments.
Keywords: *stored-product insects, acoustic control, solar energy, sustainable storage, non-chemical pest management*

Introduction

Stored-product insect pests cause significant postharvest losses worldwide, particularly in grain storage systems, where they reduce both the quality and quantity of stored commodities. Insect species such as *Trogoderma granarium, Callosobruchus maculatus, Bruchus rufimanus, Rhyzopertha dominica, Sitophilus oryzae,* and *Tribolium* spp. are responsible for direct damage through feeding and indirect losses through contamination and nutrient degradation (Arbogast, 1991; Mason and McDonough, 2012). Traditional pest control strategies have heavily relied on chemical insecticides and fumigants. However, growing concerns about pesticide resistance, chemical residues in food, and environmental degradation have accelerated the global search for non-chemical, sustainable alternatives (Rayees Ahmad et al., 2021; Taylor, 1994; Murdock et al., 2019; Rumbos and Athanassiou, 2022).

Ultrasound, defined as sound waves above 20 kHz, has emerged as a promising tool for pest control. Laboratory studies have shown that ultrasound can interfere with insect behavior, disrupt communication, and reduce reproductive success or survival (Huang et

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al., 2003; Habashy et al., 2018). For instance, *Plodia interpunctella* exposed to ultrasound exhibited impaired mating and larval development, while *Spodoptera littoralis* larvae demonstrated reduced feeding behavior. These effects suggest that ultrasound can serve as a behavioral or physiological disruptor with minimal environmental impact (Amrine and Jarabek, 1983; Gerhardt and Huber, 2003; Mankin, 2019). Recent advances in acoustic technologies have reinforced the potential of ultrasound in postharvest entomology, particularly when combined with renewable energy systems (Zhang et al., 2021; Almasi et al., 2023).

Despite this potential, existing ultrasonic pest control devices face critical limitations. Many lack rigorous scientific validation and are not tailored for specific insect targets or environmental conditions. Most commercial units do not optimize key variables such as frequency range, exposure duration, or sound directionality, and their design often overlooks real-world energy constraints and storage infrastructure needs (Ibrahim et al., 2013; Mankin et al., 2021). Furthermore, limited testing under controlled conditions makes it difficult to assess their practical effectiveness or scalability (Aflitto and DeGomez, 2015; Dryden et al., 1989).

In response to these limitations, the present study introduces a solar-powered ultrasonic device designed specifically for stored-product pest management. The system integrates three-directional (3D) ultrasound emission with a Phase-Locked Loop (PLL) frequency generator for precise and programmable frequency control. Unlike existing commercial devices, the novelty of this system lies in its renewable-powered design, energy efficiency, and adaptability to real storage environments, thus addressing the dual gap of scientific validation and energy sustainability in ultrasound-based pest control. The study evaluates its effectiveness against six economically significant insect species, using various frequency levels, exposure times, and speaker configurations. The results aim to provide a validated, renewable-powered, and environmentally sound alternative to chemical insecticides—supporting the advancement of sustainable pest control in postharvest grain storage systems.

Materials and methods

Device fabrication and configuration

A solar-powered ultrasonic device was designed and constructed to evaluate its efficacy against stored-product insect pests. The core electronic circuit (*Fig. 1*) was built using a phase-locked loop (PLL) integrated circuit (LM567), which enabled precise generation of ultrasound frequencies ranging from 10 to 104 kHz. The circuit included three output amplifiers, each connected to a piezoelectric tweeter speaker mounted on a 3D axis frame, allowing sound propagation along the X, Y, and Z axes. This three-directional configuration ensured broader ultrasound coverage within the treatment environment.

Power to the system was supplied by a 12 V, 20 W polycrystalline solar panel. Output parameters—including voltage, current, sound intensity, and waveform stability—were monitored using voltmeters, ammeters, a calibrated energy meter, a sound level meter, and an oscilloscope (Tektronix TPS 2024), respectively. Ultrasound intensity was calibrated using a handheld digital sound level meter (dB scale) placed at fixed distances (10, 15, and 20 cm) from the speaker outlets to ensure consistent acoustic exposure across treatments. A variable resistor (potentiometer) enabled fine-tuning of output frequency.

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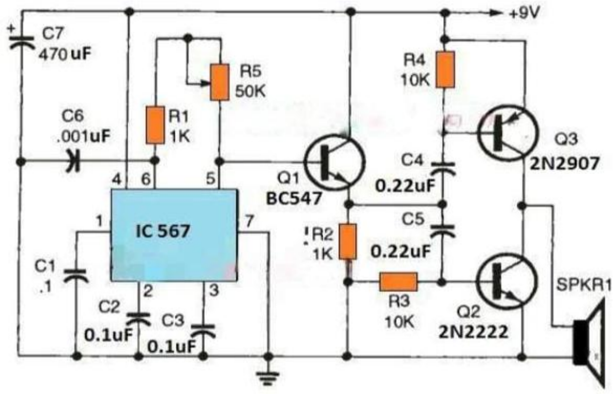

Figure 1. *Schematic diagram of the fabricated solar-powered ultrasonic device, including the LM567 PLL-based frequency generator and three-directional speaker output (X, Y, and Z axes)*

Insect source and rearing conditions

Six common storage insect pests were tested: *Trogoderma granarium, Callosobruchus maculatus, Bruchus rufimanus, Rhyzopertha dominica, Sitophilus oryzae,* and *Tribolium* spp. All insects were obtained from the Department of Stored Product Pests, Sakha Research Station, Agricultural Research Centre, Kafrelsheikh, Egypt. Colonies were maintained for at least three generations under controlled laboratory conditions: temperature 26 ± 1°C, relative humidity 60 ± 5%, and a 12:12 light–dark photoperiod. These environmental parameters were continuously monitored using calibrated digital thermohygrometers. Only healthy, active adults aged 7–10 days post-emergence were selected for bioassays.

Experimental design and replication

Experiments were conducted in transparent plastic chambers (25 × 15 × 10 cm) covered with mesh lids to permit ultrasound penetration. In each trial, 30 adult insects of a single species were placed into a chamber with a small quantity of their preferred substrate. The ultrasonic device was positioned 15 cm away from the chamber. Experiments were performed in enclosed laboratory rooms, and researchers used appropriate hearing protection when calibrating or monitoring the device.

Ultrasound exposure trials were conducted at three frequency levels (40, 80, and 104 kHz), three speaker configurations (1, 2, or 3 speakers), and three exposure durations (5, 10, and 15 min). Thus, each species underwent 27 different treatment combinations, totaling 162 distinct trials across all six species. Each treatment was replicated three times with 30 insects per replicate. A summary of the experimental design is presented in *Table 1*.

Table 1. *Experimental treatment combinations for ultrasound bioassays of six stored-product insect species*

Factor	Variables
Insect species	*T. granarium, C. maculatus, B. rufimanus, R. dominica, S. oryzae, Tribolium* spp.
Ultrasound frequency	40 kHz, 80 kHz, 104 kHz
Exposure duration	5 min, 10 min, 15 min
Speaker configuration	1 speaker (X-axis), 2 speakers (X and Y axes), 3 speakers (X, Y, Z axes)

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A completely randomized design (CRD) was used. Each treatment (frequency × duration × speaker configuration) was replicated three times per insect species. Each replicate consisted of one test chamber containing 30 insects under identical treatment conditions. A corresponding control group (unexposed to ultrasound) was included for every treatment and species to assess baseline mortality.

Mortality and behavioral assessment

Insect mortality was assessed 24 h after exposure. Individuals were considered dead if they failed to respond to gentle probing with a fine brush. Mortality assessments were conducted by independent observers who were blinded to the treatment groups in order to reduce potential bias.

Although not quantitatively analyzed in this study, insect clustering or movement away from the ultrasound source was recorded qualitatively during exposure as an indicator of possible repellency or stress behavior. These observations will guide future studies on behavioral quantification using video tracking or automated movement analysis.

Power and energy consumption

The device's power (W) and energy (Wh) consumption were measured at each frequency and speaker configuration during 15-min operational cycles. These values were recorded using an inline digital wattmeter to assess feasibility for solar-powered operation in field or on-farm storage environments.

Statistical analysis

Data were analyzed using factorial one-way Analysis of Variance (ANOVA) to evaluate the effects of ultrasound frequency, exposure duration, and speaker configuration on insect mortality. In addition, potential statistical interactions between these factors were tested. Prior to analysis, assumptions of normality and homogeneity of variance were examined using Shapiro–Wilk and Levene's tests, respectively. Where significant differences were detected ($p < 0.05$), Tukey's HSD post hoc test was applied for pairwise comparisons. Statistical analyses were conducted using SPSS v25.0 (IBM Corp., Armonk, NY, USA).

Results

Effect of exposure time on insect mortality

Exposure duration significantly influenced mortality rates in all six tested insect species. As exposure time increased from 5 to 15 min at a fixed high frequency (104 kHz) and a three-speaker configuration, mortality rose markedly. One-way ANOVA confirmed the significance of exposure time ($F = 18.24$, $df = 2$, $p < 0.001$). Control groups exhibited consistently low mortality (ranging from 0% to 5%) across all treatments, confirming that observed effects were attributable to ultrasound exposure rather than environmental or handling factors. For instance, mortality in *Tribolium spp.* increased from 20% at 5 min to 100% at 15 min (*Fig. 2*).

Similar trends were observed for *Sitophilus oryzae*, *Bruchus rufimanus*, *Trogoderma granarium*, and *Callosobruchus maculatus*, which all exhibited significantly higher mortality at 15 min compared to shorter exposure times, with most reaching full or near-

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complete mortality. In contrast, *Rhyzopertha dominica* showed a relatively lower maximum mortality of 80% at 15 min under the same conditions, indicating a comparatively higher tolerance to ultrasound exposure. Nevertheless, this mortality level was still significantly greater than those recorded at shorter durations, reflecting the general trend of increasing efficacy with longer exposure.

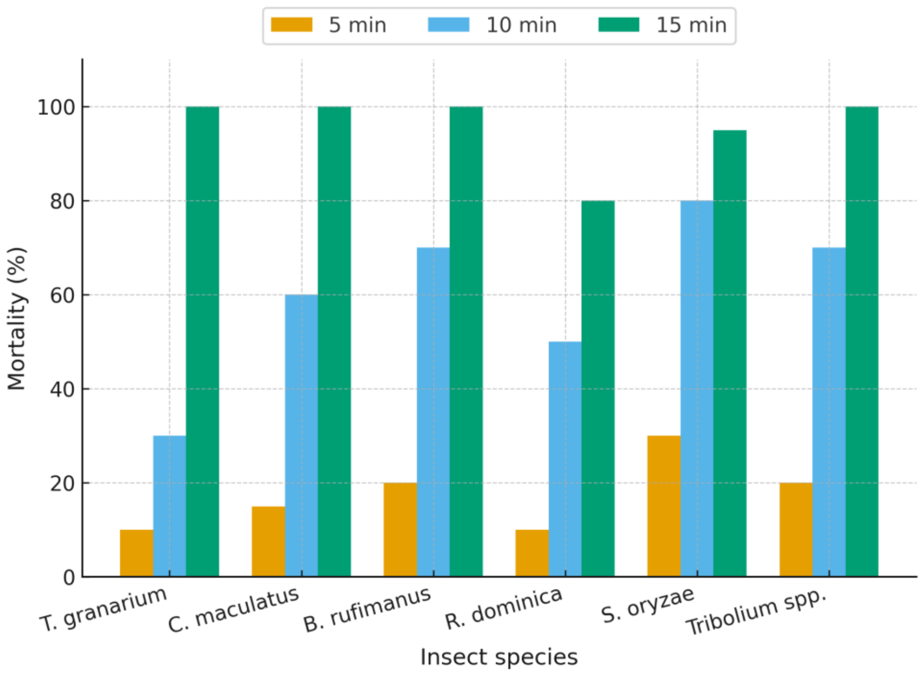

Figure 2. *Mortality (%) of six stored-product insect species exposed for 5, 10, and 15 min at 104 kHz using a three-speaker configuration. Values represent mean ± SE of three replicates (n = 30 insects per replicate)*

Effect of ultrasound frequency on mortality

Ultrasound frequency had a statistically significant effect on insect mortality ($F = 21.67$, $df = 2$, $p < 0.001$). The highest mortality was consistently recorded at 104 kHz across all species, whereas mortality at 40 kHz remained low, even under extended exposure. At 40 kHz with a single speaker and 15-min exposure, mortality remained low across all species. *Trogoderma granarium* and *Rhyzopertha dominica* showed complete resistance (0%), while mortality reached only 10% in *Callosobruchus maculatus*, 20% in *Bruchus rufimanus*, 15% in *Sitophilus oryzae*, and 25% in *Tribolium spp.* as shown in *Figure 3*.

In contrast, 15-min exposure at 104 kHz using three speakers resulted in mortality exceeding 90% in five of the six species as shown in *Figure 4,* confirming the greater lethality of high-frequency, multidirectional ultrasound.

Effect of sound directionality (speaker configuration)

The number of active speakers significantly influenced mortality ($F = 15.89$, $df = 2$, $p < 0.01$). The three-speaker (3D) setup consistently yielded the highest mortality rates. Insects exposed to 104 kHz ultrasound using this configuration exhibited significantly higher death rates than those exposed using one or two speakers.

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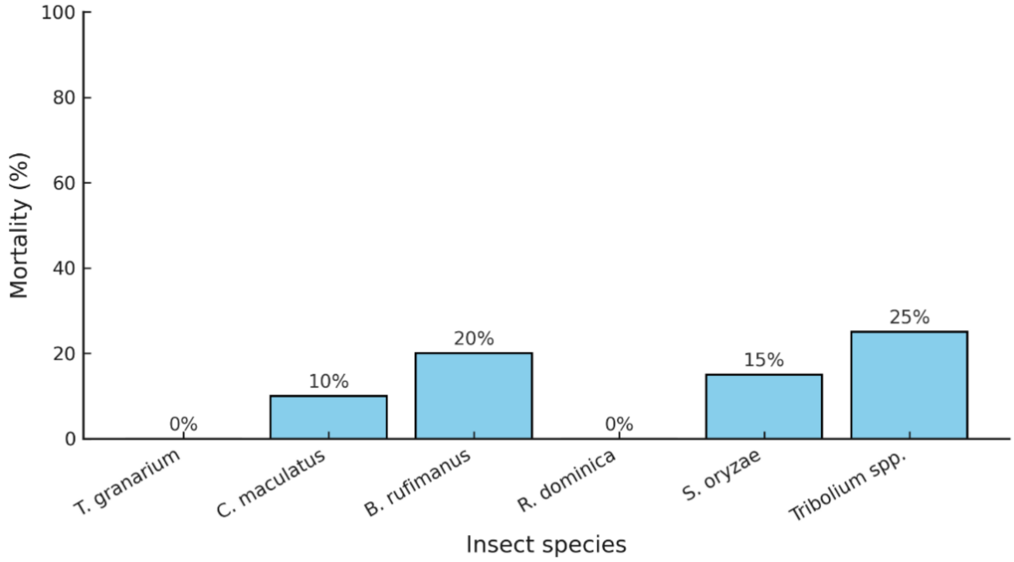

Figure 3. *Mortality (%) of six stored-product insect species after 15-min exposure to 40 kHz ultrasound using a single-speaker configuration. Values are means ± SE of three replicates*

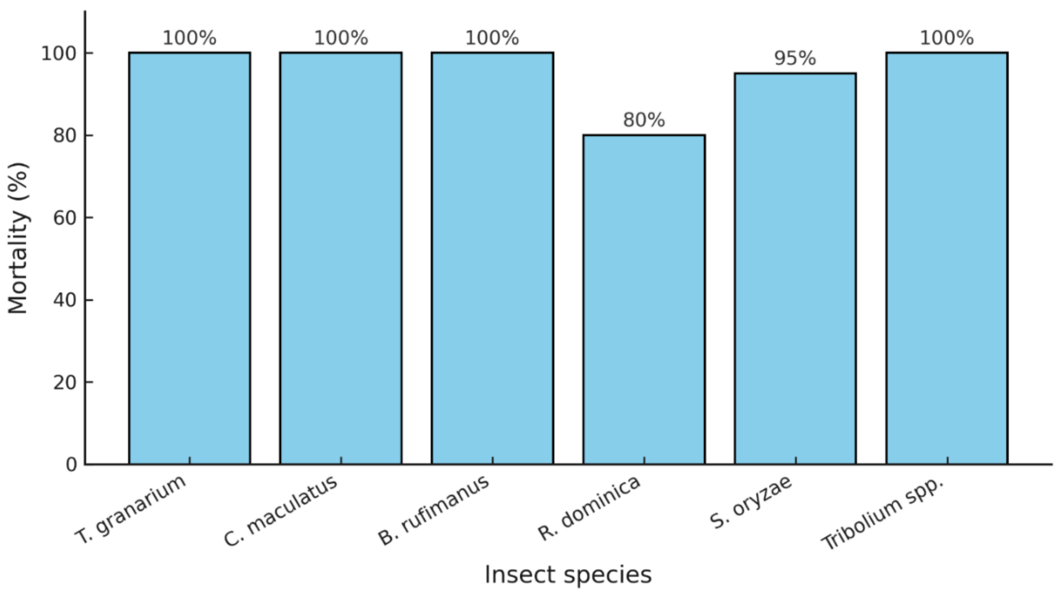

Figure 4. *Mortality (%) of six stored-product insect species after 15-min exposure at 104 kHz using a three-speaker (3D) configuration. Values represent mean ± SE of three replicates*

Figure 5 demonstrates species-specific mortality patterns across three frequencies (40, 80, 104 kHz) at a fixed exposure time (15 min) using only one speaker. Mortality was lower across all species under this limited sound dispersion setup.

Combined effect of frequency and speaker configuration

The interaction between ultrasound frequency and sound directionality was especially pronounced across all tested species. At each frequency, the use of three speakers significantly enhanced insect mortality compared to a single speaker. Notably, at 104 kHz

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with three speakers, complete mortality (100%) was achieved in *C. maculatus*, *B. rufimanus*, *T. granarium*, and *Tribolium spp.*, while *S. oryzae* reached 95% and *R. dominica* 80%. In contrast, mortality was consistently lower at 40 and 80 kHz, particularly under one-speaker treatments. These results demonstrate that both increasing frequency and improving sound distribution via multiple speakers synergistically enhance insect control (*Fig. 6*).

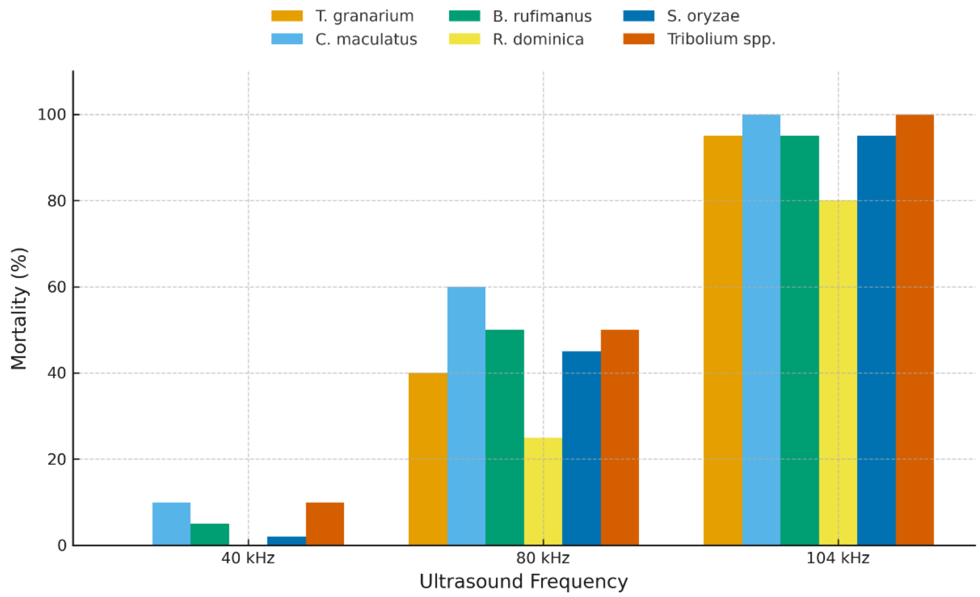

***Figure 5.** Mortality (%) of six stored-product insect species exposed for 15 min at three ultrasound frequencies (40, 80, 104 kHz) using a single-speaker configuration. Values represent mean ± SE of three replicates*

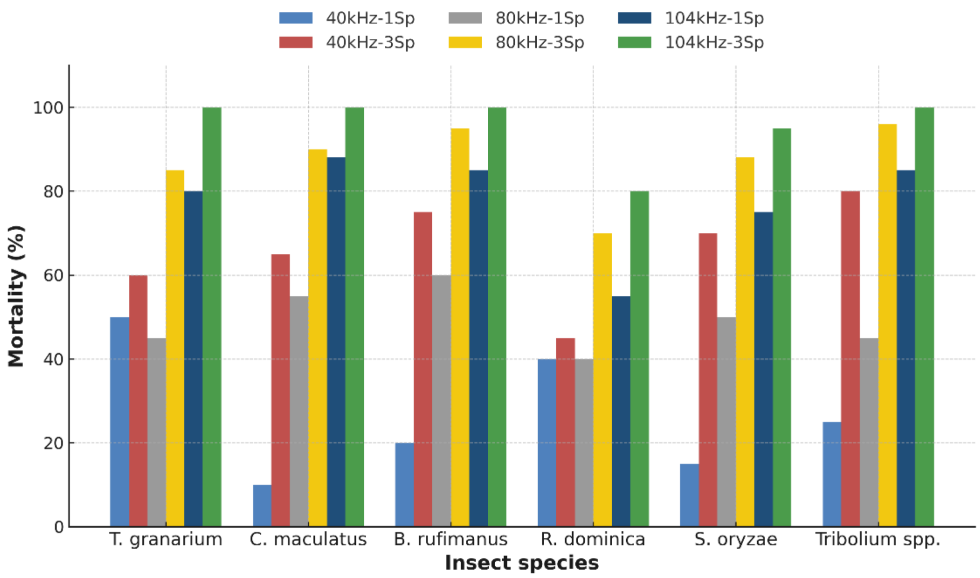

***Figure 6.** Mortality rates (%) of six stored-product insect species exposed to ultrasound at three frequencies (40, 80, and 104 kHz) for 15 min under one- and three-speaker configurations. Values represent mean ± SE of three replicates*

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In contrast, using only one speaker at the same frequency and duration led to markedly lower mortality rates, confirming the importance of multi-directional sound delivery (*Fig. 7*).

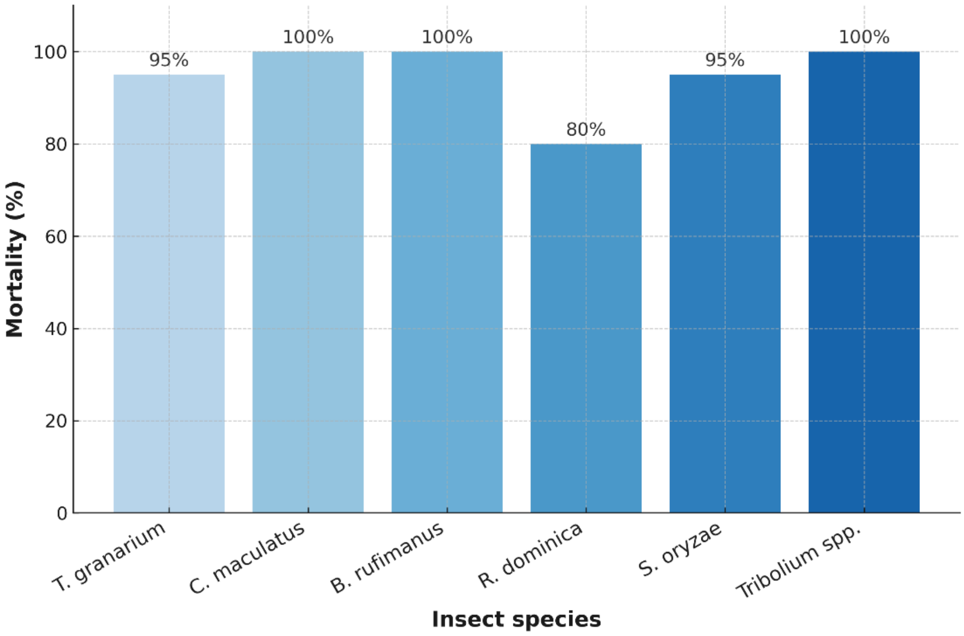

Figure 7. *Mortality (%) of six stored-product insect species after 15-min exposure to 104 kHz ultrasound using a single-speaker configuration. Values are means ± SE of three replicates*

Power and energy consumption of the device

The device's energy demand increased with both ultrasound frequency and the number of active speakers. At 104 kHz and with all three speakers activated, power reached 21.15 W and energy consumption rose to 5.28 Wh over a 15-min cycle. In contrast, the same setup at 40 kHz consumed only 0.49 Wh (*Table 2*).

Table 2. *Power (W) and energy consumption (Wh) measured at 15 min of exposure using a three-speaker setup across different ultrasound frequency levels*

Insect species	Power, W			Energy, W.h		
	40 khz	80 khz	104 khz	40 khz	80 khz	104 khz
Trogoderma granarium	0.002	9.58	21.15	0.49	2.359	5.287
Callosobruchus maculatus	0.002	9.58	21.15	0.49	2.359	5.287
Bruchus rufimanus	0.002	9.58	21.15	0.49	2.359	5.287
Rhyzopertha dominica	0.002	9.58	21.15	0.49	2.359	5.287
Sitophilus oryzae	0.002	9.58	21.15	0.49	2.359	5.287
Tribolium spp.	0.002	9.58	21.15	0.49	2.359	5.287

Values were identical for all tested insect species; data shown are representative

Table 3 presents the power and energy consumption measured for different speaker configurations. As frequency increased from 40 to 104 kHz, energy demand rose

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exponentially, reflecting the technical trade-off between efficacy and sustainability. presents the power and energy consumption measured for different speaker configurations.

Table 3. *Power (W) and energy consumption (Wh) across different speaker configurations (1, 2, and 3 speakers) at 104 kHz over a 15-min exposure period*

Insect species	Power, W			Energy, W.h		
	Speaker 1	Speaker 1 + 2	Speaker 1 + 2 + 3	Speaker 1	Speaker 1 + 2	Speaker 1 + 2 + 3
Trogoderma granarium	0.54	14.76	21.15	0.16	3.69	5.287
Callosobruchus maculatus	0.54	14.76	21.15	0.16	3.69	5.287
Bruchus rufimanus	0.54	14.76	21.15	0.16	3.69	5.287
Rhyzopertha dominica	0.54	14.76	21.15	0.16	3.69	5.287
Sitophilus oryzae	0.54	14.76	21.15	0.16	3.69	5.287
Tribolium spp.	0.54	14.76	21.15	0.16	3.69	5.287

Values were identical for all tested insect species; data shown are representative

Observed repellency behavior (qualitative)

During exposure trials, qualitative observations indicated that several species, including *C. maculatus*, *B. rufimanus*, and *Tribolium* spp., exhibited avoidance behavior at 104 kHz. These insects clustered in chamber corners, suggesting a sublethal repellent effect. In contrast, *R. dominica* remained largely inactive regardless of treatment. While not statistically analyzed here, these behaviors warrant future quantitative assessment.

Discussion

This study demonstrated the effectiveness of high-frequency ultrasound, particularly at 104 kHz, in controlling six key stored-product insect species under controlled laboratory conditions. Mortality was significantly influenced by ultrasound frequency, exposure duration, and the spatial configuration of sound delivery. The highest efficacy was observed when ultrasound was emitted through a three-directional (3D) speaker setup for 15 min at 104 kHz, under which complete mortality was recorded in four species (*C. maculatus*, *B. rufimanus*, *T. granarium*, and *Tribolium* spp.), while *S. oryzae* approached complete mortality (95%) and *R. dominica* exhibited the lowest, though still substantial, mortality (80%). These findings provide statistical evidence (ANOVA followed by Tukey's test, $p < 0.05$) that ultrasound can serve as a non-chemical pest control strategy for postharvest grain storage.

The enhanced efficacy observed at higher frequencies and longer exposure times is consistent with prior laboratory studies. For instance, Huang et al. (2003) reported that ultrasound disrupted mating and larval development in *P. interpunctella*, while Habashy et al. (2018) demonstrated reduced feeding in *S. littoralis*. Our results also align with Dryden et al. (1989), who documented acoustic mortality in fleas, though they highlighted variability across species. Importantly, the present work expands on these studies by systematically testing six major stored-product pests under standardized conditions and introducing a validated solar-powered system—addressing a key gap where most prior devices lacked rigorous evaluation (Aflitto and DeGomez, 2015; Mankin et al., 2021).

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A critical factor contributing to success was the use of a 3D speaker configuration. Unlike unidirectional designs, which can create acoustic “shadow zones,” the 3D arrangement emitted ultrasound along X, Y, and Z axes, generating a more uniform acoustic field and reducing areas of insufficient exposure. Eliopoulos et al. (2015, 2016) similarly showed that optimizing spatial sound delivery enhanced suppression of beetle infestations in grain bins. Mankin et al. (2011, 2012) also stressed the importance of uniform sound distribution for maximizing acoustic disruption. By integrating PLL-based control, our device provided flexible frequency management that could be adapted to different species or environmental contexts—an advantage over fixed-frequency commercial devices.

The device’s low energy demand (<22 W) and successful integration with a 20 W solar panel highlight its suitability for resource-limited or off-grid settings. Unlike chemical fumigants, ultrasound leaves no residues, poses no risk of resistance buildup, and can be seamlessly integrated into Integrated Pest Management (IPM) strategies that prioritize ecological safety (Rayees Ahmad et al., 2021; Taylor, 1994). Compared with conventional alternatives, this approach provides both economic feasibility (through low operating costs) and environmental compatibility (renewable energy use and absence of pollutants).

Beyond mortality, exposure also induced behavioral responses: *C. maculatus*, *B. rufimanus*, and *Tribolium* spp. frequently clustered in corners or moved away from the ultrasound source, indicating stress or repellency. Although qualitatively observed, such behaviors suggest sublethal disruption that could reduce colonization or feeding pressure. Similar effects have been reported in *P. interpunctella* (Huang et al., 2003) and *S. littoralis* (Habashy et al., 2018). Future studies should quantify these responses using behavioral tracking systems to better understand ultrasound’s deterrent potential.

Despite promising results, two limitations must be considered. First, acoustic propagation is likely to differ in large silos where reflections, grain density, and obstructions alter sound transmission. Second, insects may habituate to continuous or repetitive ultrasound (Payne and Shorey, 1968). Our PLL design allows randomized or pulsed signals, which could reduce habituation, but this requires empirical validation under long-term and field conditions. Incorporating acoustic modelling, sensor-based monitoring, and field-scale validation will be critical for translating laboratory efficacy into commercial practice.

Overall, this study provides novel, statistically validated evidence that solar-powered, multidirectional ultrasound can suppress major storage pests with high efficiency, low energy cost, and environmental safety.

Conclusion

This study demonstrates that a solar-powered ultrasonic device, particularly at 104 kHz with a three-dimensional speaker setup, can achieve high mortality and observable repellency in six major stored-product insect pests under laboratory conditions. The system’s low power demand (<22 W), solar compatibility, and ability to reduce acoustic “shadow zones” highlight its potential as a sustainable, non-chemical alternative within Integrated Pest Management (IPM) frameworks. While effective in controlled settings, future research should validate performance in bulk storage environments, optimize acoustic field distribution, and test variable signal patterns to prevent habituation and ensure long-term efficacy.

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