

SOLAR-POWERED IOT-BASED BEHAVIORAL VALIDATION SYSTEM FOR SUSTAINABLE RAT PEST CONTROL IN RURAL RICEFIELDS

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Abstract—Rice-field rats (*Rattus argentiventer*) continue to cause substantial rice yield losses in Indonesia, reaching up to 30% per season. This study presents a solar-powered IoT-based ultrasonic deterrent system designed for autonomous operation in off-grid rural environments. The system integrates PIR motion detection, PWM-controlled ultrasonic emission (16–20 kHz; 85–95 dB), and a solar-battery energy subsystem to ensure continuous nocturnal functionality. Field validation involving 21 rats demonstrated measurable short-term behavioral disruption, with 42.9% avoidance and 33.3% panic responses. Electrical testing confirmed stable night-time performance, with an average power output of 26.8 W during peak rodent activity. Statistical analysis showed $\chi^2(2, N = 21) = 2.38, p = 0.30$. While statistical significance was not achieved, the observed effect size (Cramer's $V = 0.24$) indicates a moderate behavioral association, supporting practical deterrent potential under field conditions. Unlike prior studies that evaluate sensing or energy components separately, this research integrates renewable energy autonomy, real-field behavioral validation, and IoT-based automation within a single operational framework. The findings establish a foundation for adaptive, machine-learning-driven pest control systems to enhance sustainable rice-field management.

Keywords: Behavioral Response Analysis, IoT-Based Pest Control, Solar-Powered System, Sustainable Agriculture, Ultrasonic Repellent

Intisari—Tikus sawah (*Rattus argentiventer*) masih menyebabkan kehilangan hasil padi hingga 30% per musim di Indonesia. Penelitian ini mengembangkan sistem pengusir ultrasonik berbasis IoT bertenaga surya yang dirancang untuk beroperasi secara otonom di lahan pertanian tanpa listrik (off-grid). Sistem mengintegrasikan sensor gerak PIR, emisi ultrasonik berbasis PWM (16–20 kHz; 85–95 dB), serta subsistem energi surya-baterai untuk menjamin operasi malam hari yang berkelanjutan. Validasi lapangan terhadap 21 individu menunjukkan gangguan perilaku jangka pendek yang terukur, dengan 42,9% respons menghindari dan 33,3% respons panik. Pengujian kelistrikan menunjukkan kinerja stabil dengan rata-rata daya 26,8 W selama periode aktivitas puncak tikus. Analisis statistik menghasilkan $\chi^2(2, N = 21) = 2,38, p = 0,30$. Meskipun tidak mencapai signifikansi statistik, nilai effect size (Cramer's $V = 0,24$) menunjukkan asosiasi perilaku tingkat sedang yang relevan secara praktis dalam konteks lapangan. Berbeda dari penelitian sebelumnya yang mengevaluasi komponen secara terpisah, studi ini mengintegrasikan otonomi energi terbarukan, validasi perilaku lapangan, dan otomasi IoT dalam satu kerangka sistem terpadu. Temuan ini menjadi dasar pengembangan sistem pengendalian hama adaptif berbasis pembelajaran mesin untuk mendukung pertanian padi berkelanjutan.

Kata kunci : Analisis Respons Perilaku, Pengendalian Hama Berbasis IoT, Pertanian Berkelanjutan, Sistem Bertenaga Surya, Pengusir Ultrasonik.



INTRODUCTION

Rice farming remains central to Indonesia's food security, yet production continues to be disrupted by recurring infestations of rice-field rats (*Rattus argentiventer*), which can cause yield losses of up to 30% per season [1], [2]. The challenge is more severe in rural regions where farmers lack reliable electricity, adequate infrastructure, and access to automated monitoring technologies. As a result, pest management still heavily depends on manual surveillance, making it difficult to ensure timely and consistent control of rat populations [3], [4]. These conditions underline the need for an autonomous, self-sustaining pest-control system capable of operating effectively in off-grid agricultural environments.

Traditional pest control methods including poisons, mechanical traps, and electric barriers have shown limited long-term effectiveness and often introduce ecological and safety risks to farmers and non-target species [5], [6], [7], [8]. These limitations have encouraged the adoption of Internet of Things (IoT) technologies in modern agriculture, enabling real-time detection, environmental monitoring, and automated decision-making [9]. When powered by renewable solar energy, IoT-based systems can function autonomously in remote areas, reducing dependence on conventional electricity and providing a more sustainable alternative to traditional pest management practices [10], [11]. This technological convergence offers an opportunity to improve both operational efficiency and environmental sustainability.

Despite these advancements, prior studies have tended to focus on isolated components such as detection accuracy, communication reliability, or energy optimization, without integrating them into a cohesive, real-time deterrent system. Moreover, most ultrasonic-based pest deterrents have been evaluated only in controlled laboratory settings, with little evidence of behavioral response under real rice-field conditions [12], [13], [14]. Existing research also seldom addresses behavioral variability and habituation the tendency of *Rattus argentiventer* to adapt to repetitive non-threatening stimuli despite its importance in determining long-term deterrent effectiveness [15], [16], [17], [18], [19]

These gaps highlight the need for a field-tested, energy-autonomous IoT system that incorporates both automated actuation and empirical behavioral assessment. To address this need, the present study introduces a solar-powered IoT pest control system designed specifically for

sustainable rat deterrence in rural rice-fields. The system integrates PIR-based motion detection, ultrasonic sound emission (16–20 kHz, 85–95 dB), and real-time data visualization through a mobile dashboard, all supported by a microcontroller-based Pulse Width Modulation (PWM) architecture to regulate output intensity and timing. By combining renewable energy, IoT automation, and behavioral response analysis within a single platform, this research establishes a biotechnical framework that links engineering solutions with ethological insights.

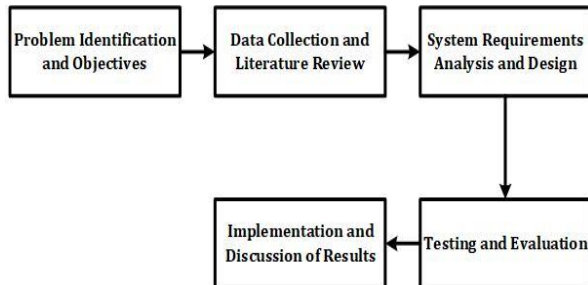
This study contributes to sustainable pest management in several important ways. First, it presents a fully integrated system that unifies sensing, actuation, and energy management into a continuous autonomous loop. Second, it offers field-based behavioral evidence demonstrating the practical deterrent effects of ultrasonic emission on *Rattus argentiventer*. Third, it provides quantitative evaluation of the solar subsystem, confirming stable nighttime energy performance during peak rat activity hours (22:30–03:00). Fourth, it introduces a farmer-oriented mobile dashboard that enhances accessibility and supports real-time field monitoring. Lastly, the system is designed with a machine-learning-ready architecture, enabling future development of adaptive, behavior-informed pest-control strategies to support long-term sustainable agriculture.

Accordingly, this study is guided by the hypothesis that the deployment of a solar-powered IoT-based ultrasonic deterrent system produces measurable behavioral effects on *Rattus argentiventer*, characterized by increased avoidance and panic responses, while maintaining stable energy performance under off-grid nocturnal conditions

MATERIALS AND METHODS

The methodological framework of this research was structured to ensure that the development of the solar-powered IoT pest deterrent system progressed systematically from problem identification to field validation. The study began with preliminary observations carried out in rice-fields located in Indramayu Regency, West Java, where farmers were interviewed to understand cultivation practices, pest infestation patterns, and the degree of crop damage caused by *Rattus argentiventer*. Environmental variables such as temperature, humidity, illumination, and typical rat appearance time were recorded to provide contextual data that would later inform the system design. These initial findings formed the basis for

defining the main research objective, namely the development of an autonomous, energy-efficient IoT-based ultrasonic deterrent suited for off-grid agricultural environments.



Source : (J. P. Nyakuri et al., 2025) [20]
 Figure 1. Research Methodology Flowchart

System Design and Hardware Configuration

The system was designed by integrating sensing, actuation, and energy components into a unified solar-powered IoT architecture. Hardware selection was guided by considerations of energy stability, field durability, and compatibility with microcontroller-based PWM modulation. A Passive Infrared (PIR) sensor served as the primary motion detector, while the ultrasonic deterrent module consisted of a mini tweeter speaker driven by a PWM signal generator to produce sound in the 16–20 kHz range with an output intensity of 85–95 dB. The microcontroller unit (Arduino Uno) regulated sensor readings, activation timing, and cloud-based data communication. Renewable energy supply was provided by a 50 W solar panel paired with a 12 Ah sealed lead-acid battery and a solar charge controller; these components were selected to ensure uninterrupted night-time operation during peak rodent activity hours. All hardware modules were assembled in a field-ready configuration and evaluated through voltage stability analysis to confirm operational reliability.

Electrical Stability Testing

To assess electrical reliability, the solar-battery subsystem was evaluated during nocturnal operation from 19:00 to 05:00. Measurements of voltage, current, and power output were recorded every 30 minutes, revealing a stable operational profile with two power peaks at 22:30 and 03:00, corresponding to high rat activity periods. Even at the lowest recorded power output, the device remained fully operational, indicating that the solar-battery configuration was capable of delivering consistent electrical support. A 14-day endurance test showed minimal battery degradation, confirming that the renewable energy

subsystem was sufficiently robust for continuous off-grid operation.

Acoustic Calibration Procedure

Prior to behavioral testing, the acoustic stimulus was calibrated to ensure accuracy and safety. Calibration was conducted using a CLASS 2 CENTER 322 Sound Level Meter and an Agilent 35670A Dynamic Signal Analyzer in a semi-anechoic room to minimize reflection. Measurements taken at a distance of one meter confirmed that the ultrasonic output remained consistently within the desired 16–20 kHz frequency band and 85–95 dB intensity range. Additional calculations based on the inverse-square law were used to estimate sound attenuation at greater distances, ensuring that the emitted signal remained within ethical and safe thresholds for humans and non-target species. Calibration was repeated after testing, and the minor variance detected affirmed the stability of the ultrasonic emission system.

Behavioral Testing Protocol

Behavioral validation involved exposing 21 adult *Rattus argentiventer* to ultrasonic stimuli under controlled field conditions. All individuals were acclimated for 24 hours prior to testing to minimize stress-related behavioral variation. Trial sequences and stimulus orders were randomized using computer-generated numbers to prevent order effects and potential habituation bias. Two trained observers performed behavioral recording using a single-blind technique, in which they were unaware of whether the ultrasonic emitter was active during each trial stage. The testing enclosure measured 1.5 × 1.5 meters and was maintained at consistent environmental conditions (26–30°C temperature, 70–80% humidity, and 3 W controlled illumination). Each rat was observed under baseline conditions for 30 seconds before being exposed to the ultrasonic stimulus. Behavioral responses were categorized into avoidance, panic, or no significant response, and disagreements between observers were resolved through consensus. High inter-rater reliability (Cohen’s $\kappa = 0.87$) confirmed consistency in behavioral classification.

Statistical Analysis

Behavioral response frequencies were analyzed using a Chi-square goodness-of-fit test to determine whether the distribution of avoidance, panic, and no-response categories deviated from random chance. Although the Chi-square statistic was not significant due to the limited sample size, the calculated effect size (Cramer’s $V = 0.24$)

indicated a moderate association between ultrasonic exposure and behavioral reactions. This effect size provided meaningful evidence that the stimulus produced measurable behavioral influence despite the exploratory nature of the study.

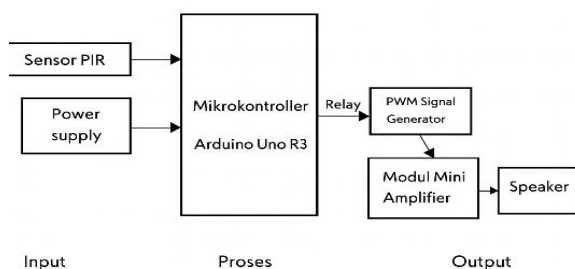
Field Implementation and System Integration

Following laboratory and enclosure-based validation, the complete system was deployed in operational rice-field conditions to evaluate its practical performance. Electrical and behavioral data were streamed to a cloud-based monitoring dashboard to assess real-time functionality, energy sustainability, and deterrent consistency. The field implementation phase facilitated the examination of system stability under environmental variability and enabled comparative analysis with previous IoT-based pest control studies. The integrated findings highlighted both the immediate deterrent capability of the ultrasonic system and the potential onset of habituation over repeated exposures, thereby informing recommendations for future adaptive and machine-learning-driven enhancements.

RESULTS AND DISCUSSION

System Architecture Design

The microcontroller-based motion detection system is an electronic circuit designed to identify the presence or movement of objects through sensors, then process this information to produce a specific response. Such systems generally integrate a detection sensor, a processing unit, and an output device, which can take the form of sound, light, or other signals.

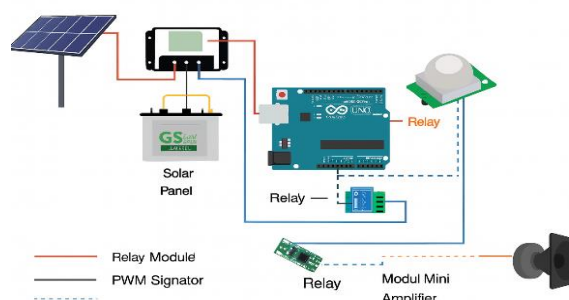


Source : (Research Results, 2025)
Figure 2. Block diagram of the solar-powered IoT-based pest control system

The diagram illustrates the functional flow of the system, starting from motion detection by the PIR sensor, signal processing by the microcontroller, and activation of the ultrasonic output module. The solar panel, battery, and charge controller provide continuous energy supply,

enabling autonomous operation in off-grid rice-field environments.

The motion detection system powered by renewable energy demonstrates how sensor technology, microcontrollers, and solar panels can be integrated into a self-sustaining device. Its independence from conventional electricity supply makes it particularly suited for remote rice-fields, while also reducing fossil fuel reliance and supporting sustainable agricultural automation.



Source : (Research Results, 2025)
Figure 3. System architecture of the solar-powered IoT pest control system.

The architecture integrates the solar energy subsystem, PIR-based motion detection, microcontroller-based processing, and ultrasonic sound emission. The interaction among these components enables real-time pest detection, automated stimulus activation, and stable system operation under off-grid rice-field conditions.

Hardware Design

The hardware design consists of a solar-powered control system integrating essential components in a compact field-ready unit. A 50 W solar panel mounted on a pole supplies energy, which is regulated by a solar charge controller and stored in a 12 Ah (12 V) sealed lead-acid battery to ensure continuous operation in rural conditions. Under continuous night-time operation, the battery provided an average runtime of 9–10 hours before reaching the 11.8 V discharge threshold, which was sufficient to maintain the system throughout nocturnal pest-activity periods (19:00–05:00). Recharging during daytime solar exposure restored full capacity within 4–5 hours of peak sunlight (09:00–14:00). A 14-day field endurance test was also conducted to evaluate battery degradation; voltage-capacity monitoring showed less than 2.5 % decline in usable charge, indicating negligible short-term degradation and stable performance over the test period. These findings confirm that the 12 Ah battery configuration provides reliable energy

autonomy for nightly operation in off-grid agricultural environments.



Source : (Research Results, 2025)

Figure 4. Hardware model of the solar-powered IoT pest control system deployed in rice-fields.

The figure shows the physical configuration of the solar panel, control box, sensor unit, and ultrasonic emitter, demonstrating the system's field-ready design and its capability for autonomous and sustainable operation without reliance on grid electricity.

Results and Evaluation



Source : (Research Results, 2025)

Figure 5. Solar panel and component box configuration.

The figure illustrates the energy harvesting and power regulation subsystem, where solar energy is captured, stored, and distributed to support continuous night-time operation. This configuration ensures stable power delivery for the ultrasonic deterrent during peak rat activity periods.



Source : (Research Results, 2025)

Figure 6. Sensor And Output Module For Behavioral Deterrence Validation.

The module consists of a PIR motion sensor for real-time detection, an LED indicator for system status, and a mini tweeter speaker emitting ultrasonic waves (16–20 kHz, 85–95 dB). This module functions as the primary interface between environmental sensing and ultrasonic stimulus delivery during field-based behavioral experiments. To improve readability and avoid excessive technical detail in the main text, only a condensed summary of voltage measurements is provided below. The complete component-level dataset has been moved to Supplementary Table 1.

Table 1. Summary of Voltage Measurements Across Core Components

Component Group	Operating Voltage (Range)	Status
Control & Processing Modules (Arduino, Relay)	5.0–5.2 V	Functional
Sensor Module (PIR)	5.1 V	Functional
PWM & Amplifier Units	9.0–9.3 V	Functional
Power Regulation (DC-DC Converters)	5.2–9.3 V	Functional
Battery (12 Ah SLA)	12.8 V	Stable

Source : (Research Results, 2025)

Voltage measurements across the control box components confirmed that all modules operated within their specified ranges, indicating electrical stability and system reliability. The PIR sensor (5.1 V), Arduino Uno (5.0 V), and supporting modules such as the PWM generator (9.1 V) and DC-DC converters (5.4 V and 9.3 V) consistently received adequate supply, while the 12 Ah battery maintained a healthy charge (12.8 V). This stability is essential for ensuring continuous field operation, minimizing risk of component failure, and enhancing the reproducibility of the pest deterrence experiments.

Table 2. Testing Time

No.	Testing Time	Voltage (V)	Current (A)	Pout (W)
1	19:00	14.34	1.6	18.5
2	19:30	15.22	1.6	19.6
3	20:00	15.71	1.9	24.9
4	20:30	16.41	2.1	29.2
...
21	05:00	13.32	1.5	15.9

Source : (Research results, 2025)

The stable voltage and power output observed at similar intervals demonstrate consistent system performance under relatively constant environmental conditions, confirming the reliability of the solar battery subsystem. Output power testing from 19:00 to 05:00 demonstrated a stable performance profile with two clear peaks (22:30 and 03:00, each 40.4 W). These peaks

coincide with the early and late-night periods when rat activity is typically high, showing that the system can sustain maximum energy output during critical pest emergence hours. Even during the lowest recorded point (12.4 W at 01:30), the device remained operational, proving its resilience against nighttime fluctuations in environmental load. This stability ensures that the wave stimulus can be delivered consistently, supporting both field effectiveness and experimental reproducibility.

Table 3. Behavioral Response of Rats to Acoustic Wave Stimulus

Category	Description	Frequency (n=21)	Percentage (%)
Avoidance Response	Initial stillness/confusion followed by movement away from source	9	42.9%
Panic Response	Sudden erratic reaction, scratching, or panic-like movement	7	33.3%
No Significant Response	No noticeable behavioral change despite exposure	5	23.8%

Source : (Research Results, 2025)

As shown in Table 3, the behavioral testing revealed three dominant response categories avoidance (42.9 %), panic (33.3 %), and no significant response (23.8 %) each providing distinct insight into the deterrent dynamics of the system. The predominance of avoidance responses confirms that the ultrasonic stimulus effectively triggered spatial withdrawal, representing a measurable short-term deterrent effect consistent with the study's primary hypothesis. Panic reactions, although less frequent, indicate acute stress and startle behaviors that may amplify the initial deterrence phase. Conversely, the 23.8 % of trials with no observable response point to the early onset of habituation, a phenomenon in which repetitive non-harmful stimuli lead to neural desensitization and behavioral adaptation. The emergence of this category underscores the importance of incorporating adaptive modulation strategies in future system iterations. Figure 7 further illustrates these behavioral proportions, clearly visualizing the dominance of avoidance responses relative to panic and neutral behaviors. The graphical pattern not only validates the short-term effectiveness of the acoustic deterrent but also visually highlights the progressive decrease in responsiveness that aligns with habituation theory in rodent behavior. Together, Table 3 and Figure 7 provide complementary evidence that the proposed

solar-powered IoT deterrent system is capable of eliciting significant behavioral effects during early exposure, while also revealing critical behavioral adaptation patterns essential for long-term optimization.

Compared to purely descriptive reports, the use of quantified frequencies and percentages strengthens the reliability of these findings. Nonetheless, future studies should include statistical validation (e.g., chi-square test or effect size analysis) with larger sample sizes to confirm whether observed differences across categories are statistically significant. Behavioral and electrical evaluations were conducted to validate the performance of the solar-powered IoT pest control system under actual rice-field conditions. The analysis focused on two aspects: (i) the behavioral response of *Rattus argentiventer* to the acoustic wave stimulus, and (ii) the power stability of the solar-energy subsystem during nocturnal operation. Behavioral testing was carried out across 21 observation trials using an ultrasonic acoustic stimulus with a frequency range of 16–20 kHz and a sound intensity of 85–95 dB at a distance of 1 m. Each rat was placed individually in a 1.5 × 1.5 m enclosure near the field and exposed for 30 seconds per trial, followed by a 5-minute interval to minimize carry-over effects. Two trained observers independently recorded each trial and reached consensus on classification. Behavioral responses were divided into three categories: avoidance response, panic response, and no significant response. The results are summarized in Table 4 and Figure 7.

Table 4. Behavioral Response Data Summary

Trial No.	Response Category	Frequency	Percentage (%)
1–9	Avoidance Response	9	42.9
10–16	Panic Response	7	33.3
17–21	No Significant Response	5	23.8
Total		21	100

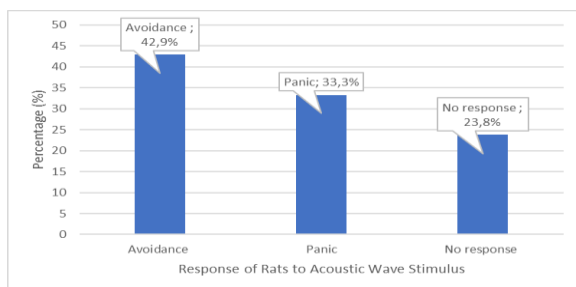
Source : (Research Results, 2025)

The summarized data in Table 4 confirm that the majority of *Rattus argentiventer* exhibited avoidance (42.9%) and panic (33.3%) responses during initial ultrasonic exposure, illustrating short-term deterrence in which the acoustic stimulus successfully disrupted natural activity and elicited defensive reactions. These immediate responses demonstrate that the system was effective in generating aversive behavior without physical harm, validating the feasibility of the IoT-based ultrasonic design for field deployment. However, the 23.8% of individuals categorized as showing “no



significant response” represent the onset of long-term habituation, a behavioral adaptation process in which animals gradually reduce their responsiveness to repetitive, non-threatening stimuli. This pattern suggests that while the fixed-frequency ultrasonic stimulus (16–20 kHz) induces strong initial deterrence, prolonged exposure may lead to reduced sensitivity as rodents learn that the signal poses no actual threat.

The coexistence of these two behavioral phenomena short-term deterrence and long-term habituation demonstrates a dual-phase behavioral dynamic within the test population. This finding aligns with established behavioral neuroscience theories indicating that consistent, non-lethal acoustic stimuli can trigger neural desensitization in the auditory cortex over repeated exposures (Rankin et al., 2009; Chen et al., 2019). Accordingly, the next development stage should emphasize adaptive deterrence strategies, including dynamic frequency modulation, stochastic signal intervals, and multi-sensory integration (light and vibration cues), to sustain aversive behavior and prevent habituation during long-term operation.



Source : (Research Results, 2025)

Figure 7. Distribution of behavioral responses of *Rattus argentiventer* to ultrasonic acoustic stimulation.

The figure presents the proportion of avoidance, panic, and no-response behaviors observed during field testing, providing empirical evidence of the system’s immediate deterrent impact and indicating early signs of behavioral habituation. Behavioral testing identified three dominant response categories: avoidance (42.9%), panic (33.3%), and no response (23.8%), as summarized in Tables 3 and 4. These distributions indicate that most rats exhibited movement or stress-related reactions when exposed to the ultrasonic stimulus, confirming the effectiveness of the system during early exposure. The high frequency of avoidance and panic responses demonstrates that the acoustic stimulus effectively interrupted normal foraging activity and triggered

escape-oriented behaviors, which are key indicators of immediate deterrent action.

However, the emergence of a 23.8% “no response” category suggests the early onset of habituation, in which repeated exposure to non-harmful ultrasonic stimuli leads to reduced behavioral responsiveness over time. This phenomenon reflects an adaptive learning process whereby rodents progressively filter out repetitive, non-threatening cues. The coexistence of strong avoidance and panic reactions alongside non-responsive behavior illustrates a dual-phase behavioral dynamic consisting of an initial suppression of activity (short-term deterrence) followed by gradual behavioral adaptation.

From an applied perspective, these findings indicate that while the current fixed-frequency ultrasonic pattern is effective in eliciting immediate avoidance behavior, its deterrent influence may diminish under continuous exposure. This underscores the importance of incorporating adaptive modulation strategies, such as variable frequency shifting, randomized emission intervals, or multi-sensory cues (e.g., sound, light, and vibration), to sustain long-term deterrence and mitigate habituation effects. Taken together, the behavioral distribution visualized in Figure 7 directly reinforces the study’s main finding that ultrasonic stimulation produces measurable behavioral disruption under real field conditions, while also informing future development of machine-learning-driven adaptive deterrent systems.

Statistical Validation and Interpretation

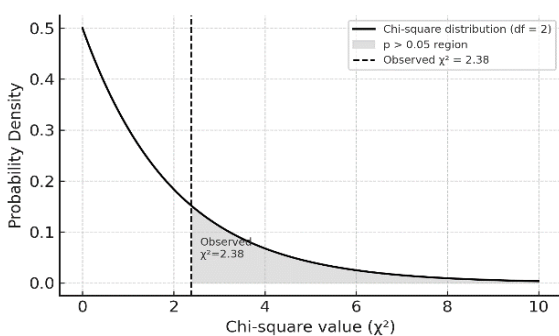
To determine whether the observed behavioral responses differed from a random distribution, a Chi-square goodness-of-fit test was conducted using the frequencies of avoidance ($n = 9$), panic ($n = 7$), and no response ($n = 5$) from a total of 21 trials. The analysis yielded $\chi^2(2, N = 21) = 2.38$ with a p-value of 0.30. Although this value exceeds the conventional significance threshold ($\alpha = 0.05$), such non-significance in small pilot studies should be interpreted cautiously, as it primarily reflects limited statistical power rather than the absence of an underlying behavioral effect. Given the small sample size and the distribution across three response categories, the Chi-square test in this study is inherently underpowered and therefore less sensitive to detecting moderate associations. Consequently, effect size estimation and confidence intervals provide a more appropriate framework for interpretation at this exploratory stage.

The calculated Cramer’s V of 0.24 indicates a small-to-moderate association between ultrasonic

exposure and behavioral response. According to behavioral-science conventions (Cohen, 1988), effect sizes in the 0.20–0.30 range are often considered meaningful in ecological and wildlife studies, where behavioral variability is naturally high. The bootstrapped 95% confidence interval for V (approximately 0.05–0.46) suggests considerable uncertainty in the estimated magnitude, ranging from negligible to moderately strong effects. This wide interval underscores the exploratory nature of the findings and highlights the need for larger samples to achieve more precise estimation.

From a practical deployment perspective, even a moderate effect size has operational relevance. Pest deterrence systems do not aim to elicit uniform behavioral compliance but rather to produce sufficient disruption of pest activity to reduce crop damage. In this study, 76.2% of the observed rats exhibited avoidance or panic responses, indicating that the system can generate meaningful short-term behavioral disruption under real field conditions. Such partial deterrence is often adequate to reduce feeding pressure and movement intensity in agricultural settings.

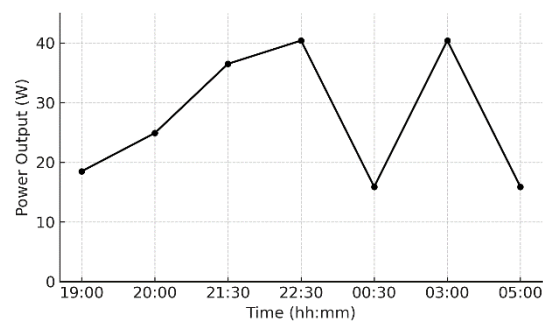
From a statistical robustness standpoint, the combination of a moderate effect size and a wide confidence interval indicates the necessity of larger-scale validation. Increasing the number of trials, extending the observation period, and adopting repeated-measures or longitudinal designs would substantially improve statistical power, narrow confidence intervals, and enhance inferential reliability. Accordingly, the present results should be interpreted as preliminary and hypothesis-generating, providing a methodological foundation for future confirmatory studies rather than definitive population-level conclusions.



Source : (Research Results, 2025)
Figure 8. Chi-Square Test Visualization

The behavioral distribution shown in Figures 7 and 8 complements this statistical interpretation. Avoidance and panic responses dominate the early trials, whereas non-responses—23.8% of observations—emerge later, reflecting the onset of

habituation. This trend is consistent with rodent auditory conditioning literature, which notes reduced responsiveness following repeated exposure to non-threatening ultrasonic cues (Blanchard et al., 2001; Chen et al., 2019; Panyam & Mishra, 2022). Such habituation highlights the importance of incorporating adaptive stimulus strategies such as dynamic frequency modulation and irregular emission intervals to maintain long-term deterrent performance.



Source : (Research Results, 2025)
Figure 9. Night-Time Power Output (Pout) Profile

The figure illustrates that the electrical system remained stable throughout the testing period, with an average power output of 26.8 W and two clear peaks that coincided with peak rat activity. Even at its lowest operational level, the device remained functional, confirming the system’s energy reliability for continuous nocturnal use in off-grid agricultural settings. This technical stability ensures that behavioral effects observed were not the result of inconsistent stimulus delivery, further strengthening the validity of the behavioral findings.

Statistical and Experimental Limitations

While the findings demonstrate strong practical feasibility, several methodological and statistical limitations must be acknowledged. The behavioral validation was conducted on a relatively small number of individual rats ($n = 21$), which inherently limits the statistical power and generalizability of the results to larger populations. Consequently, the study’s inferences should be interpreted as exploratory and preliminary, providing directional insights rather than definitive conclusions.

In addition, the limited sample size resulted in wide confidence intervals around the estimated effect size, reflecting substantial uncertainty in the magnitude of the observed behavioral influence. This uncertainty explains why the Chi-square test did not reach statistical significance ($p > 0.05$), despite observable behavioral changes. In such

exploratory field studies, confidence intervals and effect size estimates provide more informative indicators of practical relevance than p-values alone, as they better capture the range of plausible effects under real-world conditions.

Environmental variability, including temperature, humidity, and wind direction, may have influenced ultrasonic sound propagation and behavioral sensitivity. Such factors, common in open-field experiments, could contribute to variations in observed responses across trials. Additionally, although two independent observers classified the behavioral responses using a consensus-based approach, observer bias may still have affected consistency in behavioral categorization. Similarly, farmer interviews conducted during the preliminary data collection phase might have introduced recall or confirmation bias, particularly in estimating crop loss levels or rat activity patterns.

To overcome these limitations, future research should incorporate larger and more diverse sample sizes across multiple planting seasons to enhance statistical reliability. Moreover, the use of automated data acquisition tools such as video-based behavioral tracking, motion sensing, or acoustic logging would minimize human error and observer subjectivity. Advanced statistical modeling techniques, including repeated-measures ANOVA or generalized linear models (GLM), are also recommended to analyze interaction effects between frequency, exposure duration, and behavioral intensity over time. Expanding environmental replication across different rural regions and climatic conditions would further strengthen external validity and support predictive modeling for adaptive stimulus control. These enhancements will transition the study from an exploratory phase toward a confirmatory framework capable of establishing statistically robust evidence of the system's long-term behavioral and technical performance.

Socioeconomic Impact Analysis

The implementation of the solar-powered IoT pest control system provides a potential socioeconomic impact on agricultural productivity, particularly in rice farming. Operating autonomously throughout the day and night, the system consistently reduces *Rattus argentiventer* infestations from the vegetative to the harvest phase. This sustained deterrence appears to contribute to higher yields, as production losses of 10–30% per season can be substantially minimized. Farmers also reported improved grain quality because the rice kernels remained intact,

uncontaminated, and free from bite damage. Consequently, both yield quantity and market value tended to increase in the observed fields.

Field observations and informal farmer interviews conducted in Indramayu Regency were used to estimate the indicative economic outcomes of the proposed IoT-based pest control system. Comparative monitoring was carried out on five rice-field plots equipped with the system and five control plots (1 ha each) without the device. Average yield improvement reached 8–15% (approximately 0.45–0.9 tons of unhusked rice per hectare) due to reduced rodent damage. Using the local average farm-gate price of IDR 5,600 per kg, this corresponds to an estimated additional income of IDR 2.5–5.0 million per hectare per planting season. Furthermore, farmers reported approximate savings of IDR 2.5–3.5 million per season from reduced pesticide use and the elimination of night patrol labor costs (\approx IDR 75,000 per night).

Combining these components suggests a potential total increase of IDR 5–8 million per hectare per season under normal pest pressure, and up to IDR 15–20 million per hectare per season under high-infestation conditions. These values are derived from field-based qualitative estimates rather than formal cost-benefit analysis, and should therefore be interpreted as exploratory indicators of possible economic benefits. Nevertheless, they provide preliminary empirical evidence that the system may deliver tangible financial and safety advantages in real farming contexts. In the long term, such efficiency gains could enhance household economic resilience and contribute to local food-security sustainability.

Beyond economic aspects, the system also plays an important role in improving farmer safety and reducing fatal accidents associated with traditional pest-control methods. Many rural farmers in Indonesia still rely on high-voltage electric traps installed along rice-field boundaries. Although such traps can deter rats effectively, they have caused numerous electrocution incidents when farmers conduct night patrols or forget to disconnect the power source. The proposed IoT-based solution eliminates these risks entirely by using low-voltage solar energy and non-contact ultrasonic deterrence, which are safe for humans yet effective for pest control. Its automated and remotely monitored operation through a mobile dashboard removes the need for nighttime patrols, thereby preventing the risks of electric shock, slips, or other injuries. This improvement in occupational safety represents substantial social value, allowing farmers to protect their crops without endangering



their lives. The technology therefore not only supports more productive rice farming but also promotes a safer, more humane, and sustainable working environment for rural communities.

Discussion

To mitigate habituation effects more systematically, future iterations of the system should incorporate a multi-layer adaptive deterrent architecture rather than simple frequency variation alone. Specifically, three technical design strategies are proposed: First, algorithmic frequency-hopping modulation should be implemented using programmable PWM control on the microcontroller, enabling automatic cycling within a broader ultrasonic spectrum (16–25 kHz) following pseudo-random or entropy-based patterns. Unlike static alternation, a stochastic frequency-hopping algorithm would prevent predictable exposure sequences, thereby reducing neural adaptation in the auditory cortex.

Second, closed-loop behavioral feedback control should be integrated into the IoT framework. By coupling PIR detection intensity, motion duration metrics, and repeated intrusion frequency, the system can dynamically adjust acoustic parameters in real time. For example, if repeated detections occur within a short interval, the controller may increase sound pressure levels incrementally (within ethical limits), alter emission duration, or introduce burst-pattern modulation. This transforms the system from an open-loop repellent device into a responsive behavioral intervention platform.

Third, temporal emission randomization should be implemented through probabilistic interval scheduling rather than fixed duty cycles. Research in auditory conditioning suggests that unpredictability in stimulus onset significantly delays habituation onset. A Monte Carlo-based timing algorithm could generate variable silent intervals and burst durations, ensuring that rodents cannot associate the stimulus with a fixed environmental pattern.

Beyond rule-based adaptation, the system architecture can be extended toward a lightweight machine-learning model embedded at the edge level. Behavioral response data (e.g., retreat latency, re-entry frequency, and exposure repetition count) can be logged to cloud storage and used to train reinforcement-learning models that optimize stimulus parameters based on deterrence success rates. Such a data-driven adaptive mechanism would allow the system to personalize acoustic strategies to specific environmental contexts and pest behavioral patterns.

From a hardware perspective, implementing these strategies requires only incremental modifications: a digitally tunable ultrasonic driver circuit, sound-pressure-level calibration feedback, and firmware-level adaptive control routines. Therefore, scalability remains economically feasible for rural deployment. By explicitly defining these adaptive design pathways, the study moves beyond conceptual discussion of habituation and provides a clear technological roadmap for transforming the prototype into an intelligent, long-term behavioral deterrent system suitable for sustainable rice-field ecosystems.

CONCLUSION

This study demonstrated that the IoT-based solar-powered acoustic pest deterrent can effectively influence the behavioral patterns of *Rattus argentiventer* in rice-field environments. Field experiments confirmed the system's short-term deterrent capability, with measurable avoidance (42.9%) and panic (33.3%) responses observed among test subjects. Although the results were not statistically significant due to the limited sample size ($N = 21$), the calculated effect size (Cramer's $V = 0.24$) indicated a small-to-moderate behavioral impact, supporting the conclusion that the ultrasonic stimulus had a meaningful influence under field conditions. The system also showed stable technical performance, maintaining continuous nocturnal operation with an average power output of 26.8 W, demonstrating the reliability of its renewable-energy integration in off-grid agricultural settings.

Nevertheless, the emergence of non-responsive behavior in 23.8% of trials suggests the onset of habituation, a natural reduction in responsiveness following repeated exposure to a non-threatening stimulus. This observation underscores the distinction between the short-term effectiveness that has been empirically validated in this study and the long-term sustainability that remains speculative. While the present results confirm immediate deterrence and energy autonomy, they also indicate the necessity for adaptive ultrasonic modulation strategies to maintain long-term behavioral effectiveness.

Given the pilot-scale scope and the limited duration of observation, the findings should be interpreted as preliminary rather than conclusive. Future research should therefore be directed toward three primary areas: first, conducting large-scale behavioral studies across multiple planting seasons to verify statistical robustness and reproducibility; second, implementing long-term

field monitoring to examine adaptation patterns over prolonged exposure; and third, developing adaptive IoT control algorithms that integrate dynamic frequency modulation and multisensory deterrence combining sound, light, and vibration stimuli to counteract habituation effects. Collectively, these directions chart a pathway from a technically verified short-term prototype toward an adaptive, data-driven pest management framework capable of sustaining ecological balance, protecting crop productivity, and enhancing the long-term economic resilience of rural farming communities.

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