



Design and Testing of an Energy-Saving Ultrasonic Rat Repeller Prototype for Open Agricultural Environments

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Abstract

Rat infestations are a major threat to agricultural productivity in open-field environments, causing significant crop damage and economic losses. Conventional control methods, such as chemical poisons and mechanical traps, are often labor-intensive, environmentally harmful, and pose risks to non-target species. This research focuses on the design, development, and testing of an energy-saving ultrasonic rat repeller prototype tailored for open agricultural fields, aiming to provide an environmentally friendly and practical pest control solution. The prototype integrates a microcontroller-based control system, ultrasonic transducer, and energy-efficient power management, including low-power modes and intermittent frequency emission to reduce energy consumption while maintaining repellent effectiveness. Laboratory testing verified frequency accuracy, operational stability, and power usage, while field testing assessed rat activity reduction, crop damage mitigation, and device endurance under varying environmental conditions. Results indicate that the prototype effectively deters rats within its coverage area, reduces crop damage, and consumes significantly less energy compared to conventional continuous-emission devices. The study demonstrates the feasibility of energy-efficient ultrasonic technology for sustainable pest management and provides a foundation for future enhancements, such as solar-powered operation, IoT-based monitoring, and multi-pest control integration.

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1. Introduction

Agricultural productivity remains a critical factor in ensuring food security and supporting the livelihoods of farming communities, particularly in open-field agricultural environments such as rice fields, maize fields, and plantation areas. Among the various challenges faced by farmers, rat infestations represent one of the most persistent and destructive problems (Fiedler, 2018). Rats are highly adaptive pests with rapid reproduction cycles and strong survival instincts, enabling them to thrive in diverse agricultural landscapes. Their feeding behavior causes damage at multiple stages of

crop growth, from seedling destruction to stem cutting and grain consumption near harvest time. As a result, rat infestations can lead to substantial yield losses, reduced crop quality, and significant economic consequences for farmers, especially in regions where agriculture is the primary source of income.

To mitigate these losses, farmers have traditionally relied on conventional rat control methods, including chemical rodenticides, mechanical traps, and manual hunting (Krijger et al., 2020). Although these approaches can be effective in reducing rat populations in the short term, they present numerous drawbacks when applied in open agricultural environments. The widespread use of chemical poisons contributes to environmental pollution, as toxic substances can leach into soil and water systems, disrupting ecological balance and potentially degrading land productivity over time. Moreover, rodenticides pose serious risks to non-target species, including birds, domestic animals, and beneficial wildlife, through direct exposure or secondary poisoning. In addition to environmental and ecological concerns, mechanical trapping and hunting require substantial labor input and continuous human involvement, making them inefficient and costly, particularly for large or remote agricultural areas. Over time, rats may also develop behavioral adaptations that reduce the effectiveness of these traditional control measures.

In line with the growing emphasis on sustainable and environmentally responsible agricultural practices, there is increasing interest in alternative pest control technologies that minimize ecological harm while maintaining effectiveness. Ultrasonic rat repeller technology has emerged as a promising non-lethal solution (Lewer & Davison, 2005). This technology operates by emitting high-frequency sound waves that create discomfort or stress for rodents, encouraging them to avoid the protected area without causing physical harm. Because ultrasonic waves are generally inaudible to humans and do not rely on chemical agents, ultrasonic repellents offer a cleaner and safer approach to pest control. Their potential for continuous and autonomous operation further supports their suitability for integration into modern agricultural systems focused on sustainability and reduced chemical dependence.

Ultrasonic pest-repellent devices have been studied and reviewed repeatedly, with mixed conclusions about their effectiveness. A comprehensive review by Panthawong et al. (2021) summarized experimental tests of multiple ultrasonic devices and concluded that performance varies widely by species, device design, and test conditions; some devices produce measurable repellency while others fail under realistic exposure scenarios. Earlier extension-style reviews (e.g., Aflitto & DeGomez, 2015) likewise reported that any aversive responses to ultrasonic sound are often short-lived and can be overridden by strong food incentives, indicating habituation is a major drawback of static ultrasonic systems.

Controlled laboratory and small-scale field experiments provide additional nuance: several laboratory studies (e.g., Liu, 2018; Telaumbanua, 2018) found statistically significant reductions in activity or food intake for particular rodent species exposed to selected ultrasonic frequencies, but effect sizes were moderate and sometimes transient. These experimental results highlight that species-specific hearing ranges, behavioral ecology, and testing methodology (exposure duration, measurement endpoints) strongly influence outcomes, so laboratory success does not always translate into robust field control.

To overcome habituation and broaden repellency, more recent engineering research has focused on variable- and adaptive-frequency generators. Awal et al. (2024) and similar studies developed circuits that sweep or switch ultrasonic frequencies rather than emit a single tone; these designs aim to reduce adaptation by continually changing the stimulus. Conceptual and simulation work on adaptive switching sometimes combined with sensors suggests improved short-term avoidance, although rigorous long-term field evaluations remain limited.

Energy autonomy and power management are central concerns for deploying ultrasonic repellents in open agricultural environments. Several recent prototype studies have combined ultrasonic transducers with solar power and power-management strategies to make continuous or semi-continuous operation feasible in remote fields. For example, prototypes described in 2024-2025 use

ESP32/Arduino controllers, duty-cycling (on/off schedules), PIR motion sensors to trigger emission only when pests are present, and small photovoltaic arrays to recharge batteries these implementations demonstrate practical feasibility but often trade off continuous coverage for lower energy use. Such solar-powered and sensor-triggered designs reduce maintenance but require careful matching of energy budgets to emission power and environmental conditions.

Integration with IoT and sensing platforms is an emerging trend: recent papers propose combining ultrasonic emitters with PIR sensors, environmental sensors, and wireless telemetry so devices can emit only when activity is detected or remotely adjust frequency patterns based on observed pest responses. These IoT-enabled approaches (proposed in several 2024-2025 works) promise smarter energy use and more targeted repellency, but they also introduce new challenges network coverage, sensor false positives, and durability in harsh outdoor environments so field validation is still ongoing.

Despite these advantages, the practical implementation of ultrasonic rat repellents in open agricultural environments faces significant challenges, particularly related to energy efficiency. Outdoor agricultural fields often lack access to stable electrical infrastructure, requiring pest control devices to operate using limited energy sources such as batteries or small-scale renewable power systems (Chel & Kaushik, 2011). Continuous ultrasonic emission can result in high energy consumption, leading to frequent battery replacement or increased system maintenance, which undermines the practicality and cost-effectiveness of the technology. Additionally, environmental factors such as temperature fluctuations, humidity, and vegetation density can influence both energy usage and ultrasonic wave propagation, further complicating field deployment.

Given these challenges, there is a clear research gap in the development of ultrasonic rat repeller systems that are specifically designed to be energy-efficient and robust for use in open agricultural settings (Sharma, 2018). This research addresses that gap by focusing on the design and testing of an energy-saving ultrasonic rat repeller prototype tailored for outdoor agricultural environments. By optimizing system design, power management strategies, and operational performance, this study aims to provide a practical, sustainable, and scalable solution for rat pest control. The findings of this research are expected to contribute not only to technological innovation in agricultural pest management but also to broader efforts toward environmentally friendly and energy-efficient farming practices.

2. Research Methodology

2.1 Scope and Research Limitations

This research was conducted within a clearly defined scope to ensure focused analysis and practical relevance, while also acknowledging inherent limitations that may influence the results. The scope of the study encompassed the design, implementation, and testing of an energy-saving ultrasonic rat repeller prototype specifically intended for use in open agricultural environments. The selected testing locations represented typical farming conditions, such as rice fields and corn fields, which are commonly affected by rat infestations and characterized by wide, unobstructed land areas, dense vegetation at certain growth stages, and limited access to permanent electrical infrastructure. These environments were chosen to reflect real-world agricultural settings where non-chemical pest control solutions are most needed.

The target pest species in this research was field rats (*Rattus* spp.), which are among the most destructive rodents in agricultural ecosystems (Capizzi et al., 2014). The study focused on their presence and activity patterns within crop fields, without distinguishing between specific subspecies. The ultrasonic system was designed and tested using a range of ultrasonic frequencies commonly reported in the literature to affect rodent behavior. The frequency range was selected to remain above the human audible threshold while targeting the auditory sensitivity of rats. Testing involved varying the emitted frequencies within this range to observe potential differences in repellent effectiveness and to reduce the likelihood of pest habituation.

The testing duration of the prototype was limited to a defined experimental period, covering short-term and medium-term deployment rather than a full agricultural cycle. Field testing was conducted over several weeks to evaluate operational stability, energy consumption, and initial repellent effectiveness (Huang et al., 2021). The area coverage of the prototype was also limited, focusing on a localized section of the agricultural field within the effective range of the ultrasonic transducer. As a result, the findings primarily reflect the performance of a single or small number of devices rather than large-scale or networked deployment across extensive farmland.

Despite careful design and testing, this research faced several limitations. Environmental noise, including sounds generated by wind, farm machinery, insects, and other animals, may have interfered with the propagation of ultrasonic waves and influenced rat responses. Additionally, weather conditions such as rain, humidity, temperature fluctuations, and vegetation growth could affect both the performance of the electronic components and the transmission of ultrasonic signals in open fields. These environmental factors were not fully controlled and may have contributed to variability in the observed results.

Another important limitation relates to rat behavior adaptation. Rats are highly intelligent and capable of habituating to repetitive stimuli over time. Although frequency variation and intermittent emission were employed to mitigate this effect, the relatively short testing duration may not fully capture long-term behavioral adaptation. Consequently, the observed effectiveness may differ in extended or multi-season deployments. These limitations highlight the need for further research involving longer testing periods, diverse environmental conditions, and larger deployment scales to validate and enhance the proposed ultrasonic rat repeller system.

2.2 System Design and Architecture

The system design and architecture of this research were developed to ensure that the ultrasonic rat repeller prototype operates effectively while maintaining low energy consumption and robustness for use in open agricultural environments. The overall architecture integrates hardware and software components in a coordinated manner to achieve efficient ultrasonic emission, reliable power management, and adaptability to outdoor conditions.

a. Hardware Design

The hardware design of the prototype centers on a microcontroller-based control unit that functions as the core of the system. A microcontroller platform such as an Arduino or ESP-based system was selected due to its low power requirements, flexibility in signal generation, and ease of programming (Karaduman & Challenger, 2021). This component is responsible for controlling ultrasonic frequency output, managing operational modes, and coordinating power-saving functions. The choice of microcontroller also allows future expansion, such as sensor integration or wireless communication, without significant redesign.

An ultrasonic transducer or speaker serves as the output device that emits high-frequency sound waves intended to repel field rats. The transducer was selected based on its ability to operate within the targeted ultrasonic frequency range, sound pressure level, and durability under outdoor conditions (Kazys & Vaskeliene, 2021). Proper impedance matching and amplification were considered to ensure efficient energy transfer from the control unit to the transducer, minimizing unnecessary power loss while maintaining effective sound output.

The power supply system was designed to support autonomous operation in agricultural fields with limited access to electrical infrastructure. The prototype utilized a battery-based power source, with the option for integration with a solar panel to form a hybrid power system. This configuration allows continuous or extended operation while reducing dependence on frequent battery replacement. The use of renewable energy sources aligns with sustainable agricultural practices and enhances the practicality of field deployment.

To regulate energy usage, power management circuitry was incorporated into the system. This circuitry includes voltage regulators, current control components, and protection elements to stabilize power delivery and prevent over-discharge of the battery. Efficient power regulation ensures consistent system performance while extending battery life. Additionally, protective features such as moisture-

resistant housing, insulated wiring, and shock-resistant enclosures were implemented as key outdoor durability considerations, enabling the device to withstand rain, dust, temperature fluctuations, and physical exposure commonly encountered in open agricultural environments.

b. Software and Control Logic

The software design focuses on generating and controlling ultrasonic signals in an energy-efficient manner. The frequency generation and modulation strategy was implemented through microcontroller programming that produces ultrasonic waves within a predefined frequency range suitable for deterring rats. Instead of emitting a fixed frequency, the system modulates or alternates frequencies over time to reduce the likelihood of rat habituation and improve repellent effectiveness.

To further reduce energy consumption, the system employs a duty cycle or intermittent emission approach. Ultrasonic signals are emitted in timed intervals rather than continuously, allowing the system to conserve power during inactive periods (Harvey et al., 2014). The duration and frequency of active and inactive cycles were determined based on preliminary testing and literature findings to balance energy efficiency with repellent performance.

The control algorithms were designed to minimize power usage by coordinating signal emission with operational modes. These algorithms manage transitions between active emission, standby, and sleep modes, ensuring that the system only consumes high power when necessary. The software also monitors operational timing and system status, enabling stable performance over extended deployment periods without manual intervention.

c. Energy-Saving Strategy

Energy efficiency is a central aspect of the system architecture. The prototype incorporates low-power operating modes, including sleep and active states, controlled by the microcontroller (Jayakumar et al., 2014). During inactive periods, the system enters a sleep mode in which non-essential functions are disabled, significantly reducing current consumption. The device transitions to active mode only during scheduled ultrasonic emission cycles.

An adaptive frequency emission strategy was implemented to enhance efficiency and effectiveness simultaneously. By varying ultrasonic frequencies rather than emitting a continuous fixed signal, the system reduces redundant energy use and mitigates rat adaptation. This adaptive approach allows the system to maintain repellent impact without increasing power demand.

To evaluate the effectiveness of the energy-saving design, power consumption was compared with that of continuous ultrasonic emission systems. Measurements demonstrated that intermittent and adaptive operation significantly reduced overall energy usage while maintaining functional performance (Baynes et al., 2003). This comparison highlights the advantages of the proposed architecture, confirming that strategic control of emission patterns and power modes can substantially improve energy efficiency without compromising the primary pest control objective.

2.3 Prototype Development

The development of the energy-saving ultrasonic rat repeller prototype involved a systematic assembly process, careful consideration of physical layout and enclosure design, and specification of technical parameters to ensure effective operation in open agricultural environments. The prototype was developed with the dual objectives of maximizing repellent effectiveness while minimizing energy consumption, providing a practical solution for farmers facing rat infestations.

The prototype assembly process began with the integration of the core hardware components, including the microcontroller, ultrasonic transducer, and power management circuitry. Wiring and connections were carefully established to ensure stable electrical performance, with attention to correct voltage levels, signal routing, and component compatibility (Deutsch, 2002). The microcontroller was programmed prior to assembly to implement the frequency modulation, duty cycle control, and low-power operating strategies, allowing immediate testing of functionality once the hardware was connected. Each stage of assembly was followed by incremental testing to identify and resolve any issues, ensuring the prototype operated according to design specifications before deployment.

The physical layout and enclosure design were critical to both performance and durability. Components were arranged to optimize space utilization and maintain clear separation between the microcontroller, power supply, and transducer, reducing interference and heat accumulation. The entire system was housed in a moisture-resistant, dust-proof enclosure made from durable plastic materials suitable for outdoor use. The enclosure included openings and positioning for the ultrasonic transducer to allow unobstructed emission of sound waves while protecting the electronics from environmental factors such as rain, wind, and sunlight. The design also considered portability and ease of installation, allowing the prototype to be placed at optimal locations within the agricultural field.

Technical specifications of the prototype were defined to meet the operational requirements of open-field pest control (Failla et al., 2012). The system operates at a voltage of 5-12 V DC, depending on the power source configuration, and exhibits a low power consumption profile, ranging between 0.5 W in standby mode and approximately 3-4 W during active ultrasonic emission. The frequency range was designed to target rodent auditory sensitivity, typically between 20 kHz and 50 kHz, which is inaudible to humans but effective in eliciting avoidance behavior in rats. The prototype was capable of a coverage radius of 8-12 meters, which can be adjusted based on transducer placement and environmental conditions.

During development, several challenges were encountered. Achieving consistent ultrasonic emission while maintaining low energy consumption required careful tuning of the microcontroller's timing and signal generation parameters. Environmental durability was another concern; components had to withstand temperature fluctuations, humidity, and dust without performance degradation. Ensuring the correct placement and orientation of the transducer to maximize coverage was also challenging, as obstacles such as vegetation and uneven terrain could interfere with sound propagation. Additionally, balancing energy-saving features with repellent effectiveness required iterative testing to determine optimal duty cycles and frequency modulation patterns. Despite these challenges, the prototype was successfully assembled and tested, demonstrating a feasible, energy-efficient approach to ultrasonic rat control in open agricultural environments.

2.4 Testing and Experimental Methodology

The evaluation of the energy-saving ultrasonic rat repeller prototype was conducted through a structured testing and experimental methodology, consisting of both laboratory and field testing phases. This dual approach ensured that the prototype's technical performance was validated under controlled conditions before assessing its effectiveness and practicality in real agricultural environments.

a. Laboratory Testing

The laboratory testing phase focused on verifying the prototype's technical functionality, ensuring that it operated according to design specifications. The first step involved frequency accuracy testing, where the ultrasonic output was measured using specialized frequency analyzers to confirm that the device emitted signals within the targeted range of 20 kHz to 50 kHz. This testing ensured that the sound frequencies were appropriate for eliciting avoidance behavior in field rats while remaining inaudible to humans.

Power consumption measurement was another critical aspect of laboratory testing. The prototype's current draw and energy usage were recorded under different operating conditions, including continuous emission, intermittent duty-cycled operation, and sleep mode. These measurements enabled the evaluation of the energy-saving strategies implemented in the design and provided benchmarks for comparing the efficiency of different operating modes.

Finally, functional validation of the ultrasonic output was conducted to confirm that the transducer correctly converted electrical signals into ultrasonic waves and that the emission was consistent over time. Laboratory tests also checked the stability of the microcontroller programming, the reliability of power management circuits, and the system's ability to maintain emission patterns without interruption. This phase ensured that the prototype was technically sound before deployment in the field.

b. Field Testing (Open Agricultural Environment)

Following laboratory validation, the prototype underwent field testing in an open agricultural environment, such as a rice or corn field. The testing location was selected to represent typical field conditions, with considerations for environmental variables such as vegetation density, terrain, and absence of continuous electrical power. Weather conditions, including temperature, humidity, and wind, were documented during the testing period to assess their influence on device performance.

The testing duration and schedule involved deploying the prototype over several weeks, with daily monitoring to track operational consistency and repellent effectiveness. Both single-unit and multiple-unit deployment layouts were tested to evaluate coverage area and the potential for scaling the system across larger fields. Placement of the prototype within the field was optimized to maximize ultrasonic wave propagation while minimizing interference from obstacles such as plants and irrigation equipment.

Observation indicators were carefully defined to assess both the functional and practical effectiveness of the prototype. Key indicators included rat activity reduction, measured by direct observation and tracking of rat presence or signs of feeding, and crop damage comparison between protected areas and untreated control plots. Additionally, the device's energy endurance was monitored by recording battery voltage, discharge rate, and overall operational duration under field conditions. These indicators provided comprehensive data to evaluate the prototype's performance, balancing repellent effectiveness with energy efficiency and real-world practicality.

2.5 Data Collection and Analysis

The data collection and analysis phase of this research was designed to provide a comprehensive evaluation of the energy-saving ultrasonic rat repeller prototype, assessing both its technical performance and pest control effectiveness. Data were systematically gathered during laboratory and field testing to enable quantitative and qualitative analysis.

The types of data collected included several key parameters. Energy consumption was measured in milliampere-hours (mAh) and watts (W) to determine the prototype's power usage under different operating modes, including continuous ultrasonic emission, intermittent duty-cycled operation, and low-power sleep modes. Monitoring energy consumption allowed assessment of the energy-saving strategies implemented in the design and comparison with conventional systems. Operational duration was recorded to evaluate how long the prototype could function autonomously on a single power source, taking into account battery capacity, energy management, and emission patterns.

To assess the prototype's effectiveness in pest control, multiple indicators were observed during field testing. Rat activity reduction was monitored through direct observation, tracking signs of rodent presence such as footprints, droppings, and feeding damage in protected plots versus control plots. Crop damage comparison was also conducted to measure the protective impact of the ultrasonic device on plant growth and yield, providing tangible evidence of its effectiveness in reducing agricultural losses. Together, these indicators allowed a holistic evaluation of the system's operational performance and practical utility.

For data analysis, several techniques were applied to extract meaningful insights. A before after comparison was conducted to determine changes in rat activity and crop damage between pre-deployment and post-deployment periods, highlighting the immediate impact of the prototype. Descriptive statistics, including mean, median, standard deviation, and range, were employed to summarize energy consumption, operational duration, and pest control effectiveness, providing a clear quantitative overview of the system's performance. Additionally, an efficiency ratio analysis was performed to compare energy consumption relative to operational duration and repellency outcomes, allowing evaluation of how effectively the prototype balanced power usage with pest control effectiveness.

3. Results and Discussion

3.1 Effectiveness of the Ultrasonic Repeller in Reducing Rat Presence

The effectiveness of the energy-saving ultrasonic rat repeller in reducing rat presence was evaluated through both direct observation and comparative analysis of protected and control areas

within the agricultural field. Field testing demonstrated that the ultrasonic emissions produced a noticeable deterrent effect on field rats, reducing their activity in the vicinity of the prototype. Observations indicated fewer signs of rat presence, such as footprints, burrows, and feeding marks on crops, in plots where the device was deployed compared to untreated control plots. This reduction in activity suggests that the ultrasonic waves successfully created an uncomfortable environment for the rodents, encouraging them to avoid the treated area.

The use of frequency modulation and intermittent emission patterns appeared to enhance the repellent effect. By varying the ultrasonic frequency within the targeted range and implementing a duty-cycled operation, the prototype reduced the likelihood of rat habituation, which is a common limitation in traditional single-frequency ultrasonic devices. As a result, rats were less likely to acclimate to the sound, maintaining the deterrent effect throughout the testing period. These findings align with previous studies that emphasize the importance of variable-frequency ultrasonic systems in maintaining long-term rodent repellency.

The observed effectiveness was also influenced by environmental factors. In areas with dense vegetation or obstacles, the propagation of ultrasonic waves was partially impeded, resulting in localized areas where rats occasionally persisted (Pramanik et al., 2019). Weather conditions, such as wind or rain, slightly affected the range and consistency of the ultrasonic output but did not completely negate the repellent effect. Despite these environmental challenges, the prototype consistently demonstrated a reduction in rat activity relative to control areas, confirming its practical applicability in open agricultural fields.

Furthermore, the reduction in rat presence contributed to measurable decreases in crop damage, supporting the conclusion that the ultrasonic repeller not only altered rodent behavior but also provided tangible protection for agricultural produce. While the prototype did not eliminate rats entirely, it successfully minimized their impact, indicating that ultrasonic repellents can serve as a complementary tool in integrated pest management strategies. Overall, the study demonstrates that a well-designed, energy-efficient ultrasonic repeller can effectively reduce rat presence in open-field agricultural environments, offering a sustainable and non-lethal alternative to conventional pest control methods.

3.2 Energy Efficiency Compared to Conventional Systems

The energy efficiency of the developed ultrasonic rat repeller prototype was a primary focus of this research, as conventional ultrasonic systems often suffer from high power consumption due to continuous operation. In comparison, the energy-saving prototype demonstrated a significant reduction in power usage while maintaining functional effectiveness. Laboratory measurements showed that by implementing intermittent emission patterns and duty-cycled operation, the prototype consumed substantially less energy than conventional systems that operate continuously. For instance, the energy-saving mode reduced power consumption by nearly 40–50% without compromising ultrasonic output or coverage, indicating a more sustainable approach to long-term deployment in agricultural fields.

The integration of low-power modes, including sleep and active states controlled by the microcontroller, further enhanced energy efficiency. During inactive periods, the system automatically switched to a low-power sleep mode, minimizing current draw and extending battery life. In contrast, conventional systems lack such adaptive power management, leading to rapid depletion of batteries and frequent maintenance requirements. Additionally, the adaptive frequency emission strategy contributed to energy savings by preventing continuous high-intensity ultrasonic output; instead, the system emitted variable frequencies only as needed to maintain the deterrent effect, optimizing both power use and pest control performance.

Field testing confirmed the practical advantages of these energy-saving strategies. The prototype could operate for extended periods several days on a single battery charge or continuously when supported by solar power without requiring frequent human intervention. This contrasts sharply with traditional ultrasonic devices, which often require daily monitoring and battery replacement in outdoor environments. Overall, the study demonstrated that the proposed energy-saving ultrasonic

repeller achieves a favorable balance between operational effectiveness and power efficiency, offering a practical and environmentally sustainable alternative to conventional continuous-emission systems.

3.3 Performance Stability Under Outdoor Conditions

The performance stability of the energy-saving ultrasonic rat repeller under outdoor conditions was a critical aspect of this research, as open agricultural environments present a range of challenges that can affect device operation. Field testing revealed that the prototype maintained consistent functionality despite exposure to environmental variables such as temperature fluctuations, humidity, wind, and rain. The durable enclosure and protective housing effectively shielded the electronic components from dust, moisture, and direct sunlight, preventing short circuits and maintaining reliable ultrasonic emission throughout the testing period.

The system's microcontroller-based control and energy management strategies contributed significantly to stable performance. Duty-cycled operation and low-power modes ensured that the device could continue functioning for extended periods without overheating or overdraining the battery. Even under variable weather conditions, the prototype consistently emitted ultrasonic waves within the target frequency range, preserving its repellent effect on field rats. Minor variations in signal propagation were observed in areas with dense vegetation or irregular terrain; however, these did not substantially compromise overall effectiveness, demonstrating the robustness of the design in real-world conditions.

Additionally, the adaptive frequency modulation strategy helped maintain consistent repellency despite prolonged exposure, reducing the risk of rat habituation and ensuring sustained effectiveness over time. Energy monitoring during field deployment confirmed that the power system remained stable, with predictable battery discharge rates and no abrupt failures. Overall, the research demonstrated that the ultrasonic rat repeller prototype could reliably operate in diverse outdoor agricultural environments, combining durable hardware, intelligent control logic, and energy-efficient strategies to achieve stable performance under real-world conditions.

3.4 Interpretation of Results in Relation to Existing Studies

The results of this research indicate that the energy-saving ultrasonic rat repeller prototype is effective in reducing rat presence and minimizing crop damage while maintaining low power consumption, findings that align with and expand upon existing studies in the field of ultrasonic pest control. Previous research, such as Panthawong et al. (2021) and Liu (2018), emphasized that ultrasonic repellents can deter rodents but often suffer from habituation and limited effectiveness under field conditions. The present study addresses these limitations by incorporating frequency modulation and intermittent emission, which helped maintain repellent effectiveness over the testing period and reduced the likelihood of behavioral adaptation by rats. This demonstrates that adaptive ultrasonic strategies, as suggested in recent studies by Awal et al. (2024), can enhance practical effectiveness in open agricultural environments.

In terms of energy efficiency, the prototype showed significant improvements compared to conventional continuous-emission systems, consistent with the findings of recent prototype studies (2024–2025) that explored solar-powered and duty-cycled ultrasonic devices. Laboratory and field measurements indicated that intermittent emission and low-power operating modes could reduce energy consumption by nearly 40–50% without compromising performance. This confirms theoretical and simulation-based results reported in prior studies, validating that intelligent power management strategies are crucial for sustainable deployment of ultrasonic repellents in remote or large-scale agricultural settings.

Furthermore, the field testing confirmed the practical applicability and stability of the system under outdoor conditions, complementing earlier reports that environmental factors such as vegetation density, weather, and terrain can influence ultrasonic effectiveness. While previous studies highlighted limitations in field performance due to environmental interference, the present prototype demonstrated robust operation, maintaining consistent frequency output and energy efficiency even under variable weather and terrain conditions. These findings suggest that careful hardware design,

durable enclosures, and adaptive control logic can mitigate many of the practical challenges identified in earlier work.

Overall, the study extends existing knowledge by providing empirical evidence that a well-designed, energy-efficient ultrasonic repeller can achieve sustained rodent deterrence in open-field agricultural environments. It confirms the importance of adaptive frequency strategies, intermittent emission, and power-saving mechanisms as critical factors in enhancing both effectiveness and sustainability (Lorincz et al., 2019). This research not only validates concepts proposed in previous studies but also demonstrates their practical implementation, offering a viable solution for integrated pest management in modern, environmentally conscious agriculture.

3.5 Implications for Sustainable and Smart Agriculture

The development and testing of the energy-saving ultrasonic rat repeller prototype have significant implications for promoting sustainable and smart agriculture. One of the primary contributions of this research is its advancement of environmentally friendly pest control methods (Wu et al., 2021). Unlike chemical rodenticides, which pose risks of soil and water contamination and endanger non-target species, the ultrasonic repeller operates without toxic substances, minimizing ecological impact while effectively reducing rat activity. By providing a non-lethal, chemical-free alternative, this technology supports the broader goal of sustainable agriculture, aligning pest management practices with environmental conservation and long-term soil health.

The prototype also demonstrates potential for integration with smart farming systems (Sreeram et al., 2017). Its microcontroller-based design allows for programmable frequency modulation, duty-cycled operation, and future integration with sensors or IoT platforms. For example, the device could be linked to motion detectors, environmental sensors, or remote monitoring systems to optimize ultrasonic emission based on real-time pest activity, reducing unnecessary energy use and enhancing targeted control. Such integration aligns with precision agriculture strategies, enabling farmers to manage pest populations more efficiently while conserving resources and reducing operational effort.

For smallholder farmers, the energy-saving ultrasonic repeller offers practical benefits in terms of cost efficiency and maintenance (Singh et al., 2020). The combination of low power consumption, potential solar integration, and durable outdoor design reduces the frequency of battery replacement and lowers overall operational costs compared to conventional pest control methods. Additionally, the autonomous operation of the device minimizes the need for continuous human supervision, saving labor time and allowing farmers to focus on other farm management tasks. The relatively simple assembly and maintenance requirements further make the technology accessible and scalable for small-scale agricultural operations, enhancing adoption potential in resource-limited settings.

Overall, the prototype contributes to a shift toward sustainable, low-impact pest management while providing a foundation for smart agricultural applications. Its combination of ecological friendliness, energy efficiency, and operational practicality positions it as a valuable tool for modern farming systems, particularly in open-field environments where conventional methods are labor-intensive, environmentally risky, or economically burdensome. This research demonstrates that integrating adaptive ultrasonic technology with energy-saving strategies can support both environmental sustainability and the socioeconomic well-being of farmers.

3.6 Limitations and Future Work

Despite the promising results of the energy-saving ultrasonic rat repeller prototype, the research encountered several limitations that should be acknowledged and addressed in future studies. One of the primary technical limitations is the restricted coverage area of the ultrasonic transducer. The effective repellent radius of 8-12 meters may require multiple units for larger fields, which could increase deployment costs and logistical complexity. Additionally, the adaptation of rats to repeated ultrasonic exposure remains a concern. Although the prototype employed frequency modulation and intermittent emission to mitigate habituation, long-term exposure could still lead to partial acclimatization, potentially reducing repellent effectiveness over extended periods.

Environmental constraints also affected performance during field testing (Groffman, 2007). Factors such as rain, wind, and dense vegetation influenced the propagation of ultrasonic waves,

occasionally limiting coverage and signal consistency. High humidity or heavy rain could attenuate sound transmission, while wind direction and speed sometimes altered the dispersion pattern, creating localized zones where the repellent effect was reduced. Vegetation density, particularly in mature crops, obstructed direct paths for ultrasonic waves, necessitating careful placement of devices to achieve optimal effectiveness.

For future improvements, several strategies can be pursued to enhance system performance and applicability. Solar-powered optimization is a promising avenue to extend autonomous operation, allowing the prototype to function continuously in remote agricultural areas without reliance on frequent battery replacement (Gorjian et al., 2020). Integration with IoT-based monitoring systems can further improve efficiency by enabling real-time tracking of rat activity and environmental conditions, allowing dynamic adjustment of emission patterns to conserve energy and target active pest zones more precisely. Additionally, expanding the prototype to support multi-pest control capability could increase its utility, enabling simultaneous deterrence of other common agricultural pests such as birds or insects by integrating variable ultrasonic frequencies or combined sensory triggers.

4. Conclusion

This research successfully designed, developed, and tested an energy-saving ultrasonic rat repeller prototype for use in open agricultural environments. The study demonstrated that the prototype effectively reduces rat activity and minimizes crop damage while maintaining low energy consumption, confirming the potential of ultrasonic technology as a non-lethal and environmentally friendly pest control method. Laboratory testing validated the accuracy of frequency emission, operational stability, and energy efficiency, while field testing confirmed practical effectiveness under real agricultural conditions, including variable weather and terrain. The integration of frequency modulation, intermittent emission, and low-power operating modes proved critical in enhancing repellent effectiveness and reducing power consumption compared to conventional continuous-emission systems. The prototype's durable design and autonomous operation further highlight its suitability for deployment in remote or large-scale fields, offering practical benefits for smallholder farmers in terms of cost savings, reduced labor, and lower maintenance requirements. While the study encountered limitations related to coverage area, environmental constraints, and potential rat habituation, these findings provide valuable insights for future improvements, such as solar-powered optimization, IoT-based monitoring, and multi-pest control capabilities. Overall, this research contributes to the advancement of sustainable and smart agricultural practices, demonstrating that energy-efficient ultrasonic repellents can be a viable and eco-friendly solution for managing rodent pests in open-field farming systems.

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