MECOMARE, 24 (4) (2024) pp. 127-135

Published by: TRIGIN Publisher

International Journal of Mechanical Computational and Manufacturing Research

Journal homepage: www.trigin.pelnus.ac.id

Integration of the Internet of Things (IoT) into the Field Rat Pest Control System for Adaptive Ultrasonic Frequency Monitoring and Control

Hengki Tamando Sihotang[1], Roma Sinta Simbolon[2]

[1] Sistem Informasi, Uniiversitas Putra Abadi Langkat, Indonesia
[2] Institute of Computer Science (IOCSCience), Indonesia

A R T I C L E I N F O

Article history:

Received Sep 16, 2025
Revised Oct 14, 2025
Accepted Nov 30, 2025

Keywords:

Internet of Things (IoT);
Adaptive Ultrasonic Control;
Field Rat Pest Management;
Smart Agriculture;
Sustainable Pest Control.

ABSTRACT

Field rat infestations remain a major challenge in rice-based agricultural systems, causing significant yield losses and threatening the sustainability of food production. Conventional rat control methods, including mechanical traps, chemical rodenticides, and fixed-frequency ultrasonic devices, have shown limited long-term effectiveness due to labor intensity, environmental risks, and rodent habituation. This research aims to develop and evaluate an Internet of Things (IoT)based adaptive ultrasonic pest control system that enables real-time monitoring and dynamic frequency adjustment to improve the effectiveness of field rat management in rice fields. The study employed an applied experimental approach involving system design, IoT integration, field deployment, and performance evaluation. Sensor nodes were installed to monitor rat activity and environmental conditions, while ultrasonic emitters were controlled adaptively based on real-time data. Field experiments were conducted by comparing plots equipped with the proposed adaptive system and those using non-adaptive ultrasonic control. The results indicate that the IoT-based adaptive ultrasonic system achieved a sustained reduction in detected rat activity and demonstrated greater effectiveness than conventional fixed-frequency ultrasonic devices. The system also showed reliable operation under real-field conditions, although limitations related to network connectivity, environmental variability, and partial behavioral adaptation were observed. Overall, this research demonstrates that integrating IoT technology with adaptive ultrasonic control provides a viable, non-chemical, and scalable solution for field rat pest management. The findings contribute to the advancement of precision agriculture and support the development of smart and sustainable pest control systems with strong potential for real-world agricultural adoption.

Corresponding Author:

Hengki Tamando Sihotang,
Sistem Informasi,
Universitas putra abadi langkat, Indonesia
Jl. Letjen R. Soeprapto No.10, Kwala Bingai, Kec. Stabat, Kabupaten Langkat, Sumatera Utara 20814
Email: hengkitamando26@gmail.com

1. INTRODUCTION

Field rat pests represent one of the most persistent and destructive threats to agricultural productivity, particularly in rice-based farming systems. In many rice-producing regions, field rats (Rattus argentiventer) cause significant yield losses by attacking crops at multiple growth stages, from seedling establishment to grain filling(Singleton, 2003). Their high reproductive rate, nocturnal behavior, and ability to adapt quickly to environmental changes make them difficult to control using conventional methods. Recurrent rat infestations not only reduce harvested yields but also increase production costs and threaten farmers' income stability, thereby undermining food security and the sustainability of rice farming systems.

Conventional rat control methods, such as mechanical traps, chemical rodenticides, and static ultrasonic repellents, have demonstrated limited effectiveness in long-term field applications. Mechanical traps require intensive labor and continuous monitoring, making them impractical for large-scale agricultural areas(Potamitis et al., 2017). Chemical poisons, while effective in the short term, pose serious environmental and health risks, including contamination of soil and water, non-target species mortality, and the potential development of resistance within rat populations. Static ultrasonic devices, which emit fixed-frequency sound waves, often lose effectiveness over time as rats habituate to the constant stimuli, reducing their deterrent impact. These limitations highlight the inability of traditional approaches to respond dynamically to changing pest behavior and environmental conditions.

Existing ultrasonic pest control systems have been widely promoted as a non-chemical alternative for managing rodent infestations in agricultural environments(Smith & Meyer, 2015). However, most commercially available and previously studied ultrasonic devices operate using fixed or pre-set frequency ranges, emitting continuous sound waves without adjustment to pest behavior or environmental dynamics. This static approach presents a fundamental weakness, as rodents particularly field rats are highly adaptive animals capable of habituating to repetitive stimuli over time. As a result, the deterrent effect of fixed-frequency ultrasonic systems tends to diminish rapidly, limiting their long-term effectiveness in open-field agricultural settings. Furthermore, many existing systems are designed as stand-alone devices, lacking mechanisms to assess whether the emitted ultrasonic signals are producing the intended behavioral response.

Another significant limitation of traditional ultrasonic pest control systems is the absence of real-time monitoring and feedback mechanisms. Conventional devices typically operate without sensors to detect rat activity, environmental conditions, or system performance(Macdonald et al., 2021). Consequently, there is no empirical basis for adjusting control strategies in response to changing field conditions, such as variations in rat population density, crop growth stages, or weather-related factors. This lack of situational awareness prevents adaptive decision-making and leads to inefficient energy use, unnecessary sound emissions, and inconsistent pest deterrence outcomes. In large and heterogeneous agricultural landscapes, these constraints further reduce the practicality and scalability of traditional ultrasonic approaches.

In response to these challenges, there is an increasing need for pest control systems that are smart, adaptive, and environmentally friendly. An effective solution should be capable of adjusting its control strategy in real time, minimizing ecological impact while maintaining high deterrence performance. Adaptive ultrasonic control, which dynamically varies sound frequency based on pest activity and environmental factors, offers a promising alternative to static systems by reducing habituation effects. When combined with non-chemical approaches, such systems support sustainable agriculture by decreasing reliance on harmful substances and promoting ecological balance.

Field trials and reviews of ultrasonic pest repellents have produced mixed and often disappointing results. Early and mid-20th century work showed some short-term reductions in rodent activity but also rapid habituation; extension and review articles summarize that effect and caution about real-world effectiveness (Greaves & Rowe, cited in Aflitto & DeGomez, 2015). Practical evaluations and extension publications have repeatedly reported only mild aversion in rats and loss of effect over time when single-frequency devices are used.

Because habituation to fixed frequencies is a central limitation, several researchers have moved toward variable or multi-pattern ultrasonic generators. Prototype and engineering papers describe the design and testing of variable-frequency ultrasonic pest repellers (for storage pests and rodents), showing promise in lab or small-scale trials: examples include design and development studies of variable-frequency ultrasonic repellers (authors publishing in 2016-2019) and a 2024 prototype paper that explicitly aims to generate variable ultrasonic frequencies for rodent control (Awal, 2024; other engineering prototypes 2016-2018). These studies focus on circuit design, frequency sweep patterns, and short-term efficacy testing, demonstrating improved short-term disruption versus static emitters but generally lacking long-term field validation in agricultural landscapes.

Concurrently, a body of work has explored embedding sensors and simple control logic into ultrasonic systems (e.g., PIR-triggered ultrasonic units tied to microcontrollers such as Arduino/ESP32), enabling emission only when activity is detected and thus potentially reducing habituation and energy use (Pratama & Habib; multiple Indonesian engineering reports, 2018-2023). These applied studies typically describe hardware integration (PIR, microcontroller, speaker/driver) and short-term field tests in storage or small plots, showing reduced non-target activation and improved battery life, but they stop short of full autonomous adaptation based on environmental or behavioral analytics.

The rise of IoT and precision-agriculture research provides the systems and data side required to make ultrasonic pest control adaptive at scale. Reviews and surveys of IoT in agriculture describe architectures, sensor suites, communication stacks (LoRa, MQTT, cellular), and cloud analytics for crop monitoring, pest detection, and automated actuation (Rajak et al., 2023; Abu, 2022). Several recent applied papers and conference items implement IoT-based trap monitoring, bird/ insect deterrence, or general pest-repellent actuators (2020–2024), demonstrating remote monitoring, solar power integration, and remote control dashboards but few of these works explicitly combine continuous animal-behavior sensing with adaptive ultrasonic control targeted at field rats in open rice ecosystems.

Behavioral and biological studies of rats' ultrasonic vocalizations and stress responses give important context for ultrasonic deterrence strategies. Reviews of ultrasonic vocalizations and stress-induced USVs in rats characterize frequency ranges, contexts, and variability across species and life stages (Brudzynski, 2021; Venkatraman et al., 2024), highlighting that rodents perceive and produce ultrasonic signals and that responses depend on species, strain, and environmental context. These findings underscore why simple "one-size-fits-all" frequency outputs are unlikely to be optimal and why adaptive approaches that consider behavioral cues could be more effective.

The integration of the Internet of Things (IoT) into ultrasonic pest control systems offers a solution to these critical gaps. IoT enables the deployment of interconnected sensors capable of continuously monitoring rat activity and environmental parameters in real time. Through wireless communication and centralized or edge-based data processing, collected data can be analyzed dynamically to inform control decisions. When combined with adaptive ultrasonic frequency control, the system can automatically vary sound frequency patterns based on detected pest behavior and environmental context, thereby reducing habituation and maintaining deterrent effectiveness. This data-driven and responsive approach transforms ultrasonic pest control from a static deterrent mechanism into an intelligent, self-adjusting system aligned with the principles of precision agriculture.

The novelty of this study lies in the systematic integration of IoT-based real-time monitoring with adaptive ultrasonic frequency control specifically designed for field rat management in agricultural fields. Unlike previous research that primarily focuses on hardware design, laboratory testing, or short-term field trials using fixed or manually adjusted frequencies, this research proposes and evaluates an autonomous control framework that continuously adapts to real-world conditions(Diaz et al., 2020). The study contributes a comprehensive system architecture that combines sensing, communication, data processing, and adaptive actuation, as well as empirical field-based evaluation of its performance. By addressing both technological and behavioral limitations of existing systems, this research advances the state of the art in smart pest management and provides a scalable, environmentally sustainable solution for rodent control in modern agriculture.

2. RESEARCH METHOD

This research employed an applied experimental methodology to design, implement, and evaluate an Internet of Things (IoT)-based adaptive ultrasonic pest control system for managing field rat populations in rice fields(Telaumbanua & Waluyo, 2018). The methodological framework integrates system development, field deployment, data acquisition, and performance evaluation to assess the effectiveness of real-time monitoring and adaptive ultrasonic frequency control under actual agricultural conditions.

The first stage involved system design and development, focusing on the integration of hardware and software components(Tumer & Smidts, 2010). The system consisted of environmental and activity sensors (such as motion and ambient condition sensors), a microcontroller unit, ultrasonic sound emitters, and wireless communication modules. The microcontroller was programmed to collect sensor data continuously and execute adaptive control algorithms. Ultrasonic emitters were configured to operate across a range of frequencies relevant to rodent auditory sensitivity, allowing dynamic variation rather than fixed-frequency emission. Communication protocols enabled the transmission of sensor data to a cloud-based or local server for monitoring and analysis.

The second stage addressed IoT-based data acquisition and monitoring(Page et al., 2016). Sensor nodes were deployed at strategic locations within the rice field to detect rat activity and record environmental parameters such as temperature and humidity. Data were transmitted in real time through the IoT network to a centralized platform, where they were stored and visualized via a monitoring dashboard. This real-time data flow enabled continuous observation of pest activity patterns and system status, supporting both automated control and human supervision when necessary.

The third stage involved the implementation of an adaptive ultrasonic frequency control mechanism(Du et al., 2021). Based on incoming sensor data, the system dynamically adjusted ultrasonic emission parameters, including frequency range, emission intervals, and activation timing. Decision rules were defined to increase frequency variability when repeated rat activity was detected and to reduce or suspend emissions during periods of low activity, thereby minimizing energy consumption and potential habituation. This adaptive logic allowed the system to respond autonomously to changing field conditions without manual intervention.

The fourth stage consisted of field testing and experimental deployment(Barnard et al., 2015). The system was installed in selected rice field plots over a defined observation period covering critical crop growth stages. A comparative approach was used by observing plots equipped with the adaptive IoT-based system alongside plots using conventional or non-adaptive ultrasonic devices. Field observations included monitoring rat activity levels, crop damage indicators, and system operational stability. This comparative design enabled evaluation of the added value of IoT integration and adaptive control.

The final stage focused on data analysis and performance evaluation(Chiesa & Frattini, 2009). Collected data were analyzed to assess system effectiveness in reducing rat activity and crop damage, as well as to evaluate responsiveness, reliability, and energy efficiency. Performance metrics included changes in detected rat movement frequency, system uptime, communication latency, and power consumption. The results were interpreted to determine the overall feasibility and scalability of the proposed system, as well as its potential contribution to smart and sustainable agricultural pest management.

3. RESULTS AND DISCUSSIONS

3.1 Key Findings and Observed Patterns

The results of this research demonstrate that the integration of IoT-based monitoring with adaptive ultrasonic frequency control significantly improves the effectiveness of field rat pest management compared to conventional approaches. One of the primary findings is a notable reduction in detected rat activity in plots equipped with the adaptive system. Sensor data indicated a consistent decline in movement frequency and duration in protected areas, suggesting that dynamic ultrasonic emissions were more effective in deterring rats than static or non-adaptive ultrasonic devices. This pattern was particularly evident during peak nocturnal activity periods, when conventional systems typically experience reduced effectiveness.

Another key finding relates to the system's ability to mitigate habituation effects(Pellegrino et al., 2017). Unlike fixed-frequency ultrasonic devices, which showed a gradual loss of deterrent impact over time, the adaptive system maintained its effectiveness throughout the observation period. The continuous variation of ultrasonic frequencies and emission intervals prevented rats from becoming accustomed to a single stimulus pattern. This was reflected in irregular and declining activity signals following repeated exposure, indicating sustained behavioral disruption and avoidance behavior among the rodent population.

The research also revealed meaningful temporal and environmental patterns in rat activity. Sensor data showed that rat movement increased during specific time windows, particularly at night and during certain crop growth stages. Environmental factors such as humidity and temperature were observed to influence activity levels, with higher rat movement often occurring under favorable microclimatic conditions(Oosthuizen & Bennett, 2015). The adaptive control mechanism responded effectively to these patterns by increasing frequency variability and emission intensity during high-risk periods, thereby optimizing deterrence while conserving energy during low-activity intervals.

In terms of system performance, the IoT-based architecture demonstrated high operational reliability and responsiveness. Data transmission between sensor nodes and the monitoring platform occurred with minimal latency, enabling near-real-time adjustments to ultrasonic output. The system operated autonomously for extended periods with stable connectivity and minimal human intervention. Additionally, adaptive activation significantly reduced unnecessary ultrasonic emissions, leading to improved energy efficiency compared to continuously operating static systems.

Overall, the observed findings confirm that combining real-time monitoring with adaptive ultrasonic frequency control enhances both the effectiveness and sustainability of field rat pest management. The identified patterns of rat behavior, environmental influence, and system responsiveness provide valuable insights for optimizing smart pest control strategies and support the broader application of IoT-enabled solutions in precision and sustainable agriculture.

3.2 Effectiveness of Adaptive Ultrasonic Control

The findings of this research indicate that adaptive ultrasonic control is an effective approach for managing field rat pests in agricultural environments, particularly when compared to conventional static ultrasonic systems. By dynamically adjusting ultrasonic frequencies and emission patterns in response to real-time sensor data, the system was able to sustain its deterrent effect over an extended period. This adaptability directly addresses one of the major limitations of traditional ultrasonic devices, namely the rapid habituation of rodents to fixed-frequency sound emissions.

The adaptive ultrasonic control mechanism demonstrated a clear capacity to disrupt rat behavior by continuously altering acoustic stimuli. Variations in frequency range, emission duration, and activation intervals prevented rats from recognizing and adapting to a predictable sound pattern(Talwar & Gerstein, 2001). As a result, sensor-based monitoring showed a sustained reduction in rat movement and presence within protected field areas. This suggests that adaptive frequency modulation effectively maintains a level of acoustic novelty that triggers avoidance behavior in rats, thereby improving long-term control performance.

Furthermore, the effectiveness of adaptive ultrasonic control was enhanced by its responsiveness to temporal and environmental conditions. The system increased ultrasonic activity during periods of high rat movement, such as nighttime hours and critical crop growth stages, while reducing emissions during low-risk periods. This targeted activation not only improved deterrence outcomes but also minimized unnecessary sound exposure and energy consumption. Such context-aware operation underscores the advantage of adaptive control in optimizing system efficiency without compromising effectiveness.

Overall, the results confirm that adaptive ultrasonic control represents a substantial improvement over static ultrasonic pest management methods (Kalimuthu et al., 2020). By combining behavioral responsiveness with data-driven frequency adjustment, the system delivers a more reliable, efficient, and sustainable solution for field rat control. These findings support the broader application of adaptive ultrasonic technologies as a key component of smart pest management strategies in modern agriculture.

3.3 Advantages of IoT Integration in Real-Field Conditions

The integration of the Internet of Things (IoT) into field rat pest control systems offers significant advantages when applied under real-field agricultural conditions. One of the most important benefits is the capability for real-time monitoring and data-driven decision-making. Through interconnected sensors deployed across the field, IoT enables continuous observation of rat activity and environmental parameters without the need for constant manual inspection. This real-time visibility allows the system to respond promptly to changes in pest behavior and field conditions, ensuring that control actions remain relevant and effective throughout the cropping cycle.

Another key advantage of IoT integration is adaptive and autonomous system operation(Sifakis, 2018). In real-field conditions, pest activity and environmental factors are highly dynamic and unpredictable. IoT-based systems can process incoming data automatically and adjust ultrasonic control strategies without human intervention. This autonomous adaptability reduces dependence on labor-intensive field monitoring and minimizes delays in response, which are common in conventional pest management practices. As a result, the system is better suited for large-scale or remote agricultural areas where continuous human supervision is impractical.

IoT integration also enhances operational efficiency and resource optimization(Elijah et al., 2018). By activating ultrasonic emissions only when rat activity is detected or when environmental conditions indicate increased risk, the system avoids unnecessary operation. This selective activation leads to lower energy consumption and prolongs the operational lifespan of field-deployed devices, which is particularly important in outdoor environments that rely on limited power sources such as batteries or solar panels. Efficient resource use not only reduces operational costs but also supports environmentally sustainable farming practices.

Furthermore, IoT-based systems provide improved scalability and management flexibility in real-field applications. Centralized dashboards allow farmers or system managers to monitor multiple devices and field locations simultaneously. System performance, sensor status, and pest activity trends can be evaluated remotely, enabling timely maintenance and strategic planning. This scalability makes IoT-integrated pest control systems adaptable to varying farm sizes and diverse agricultural landscapes.

Overall, IoT integration significantly enhances the practicality and effectiveness of ultrasonic pest control systems in real-field conditions. By enabling real-time monitoring, autonomous adaptation, efficient resource use, and scalable management, IoT transforms traditional pest control approaches into intelligent, field-ready solutions that align with the goals of smart and sustainable agriculture.

3.4 Unexpected Results and System Limitations

Although the proposed IoT-based adaptive ultrasonic pest control system demonstrated overall effectiveness, several unexpected results and system limitations were identified during field implementation. One notable observation was the variation in system performance across different field conditions. In certain plots, rat activity reduction was less pronounced than anticipated, particularly in areas with dense vegetation or uneven terrain. These conditions appeared to influence the propagation of ultrasonic waves, reducing their effective coverage and highlighting the sensitivity of ultrasonic deterrence to physical field characteristics.

Another unexpected result was the temporary resurgence of rat activity after prolonged deployment, despite the use of adaptive frequency modulation(Vorobyov et al., 2010). While the adaptive system successfully delayed habituation compared to fixed-frequency devices, sensor data indicated that some rats gradually altered their movement patterns rather than completely avoiding the protected areas. This suggests that, although adaptive ultrasonic control can significantly reduce activity, it may not fully eliminate rat presence in open-field environments where alternative food sources and shelter remain available. Such behavioral plasticity underscores the complexity of rodent responses and indicates that ultrasonic deterrence alone may not be sufficient as a standalone solution in all contexts.

Several technical limitations were also encountered in real-field conditions(Tejedor et al., 2018). Network connectivity instability occasionally disrupted real-time data transmission, particularly in remote areas with limited communication infrastructure. Although the system was designed to operate autonomously during temporary connectivity losses, prolonged interruptions reduced the effectiveness of real-time monitoring and centralized control. Additionally, sensor performance was sometimes affected by environmental factors such as heavy rainfall, extreme humidity, and temperature fluctuations, which impacted detection accuracy and required periodic recalibration or maintenance.

Energy management presented another practical limitation(Alam & Arefifar, 2019). Despite improvements in efficiency through adaptive activation, prolonged cloudy conditions affected the performance of solar-powered components, leading to reduced operational uptime in some deployments. This limitation emphasizes the need for more robust energy storage solutions or hybrid power systems for continuous operation in variable weather conditions.

Overall, these unexpected results and limitations reveal important considerations for future system refinement. They highlight the necessity of combining adaptive ultrasonic control with complementary pest management strategies, improving sensor robustness and communication reliability, and enhancing power management for sustained field operation. Addressing these limitations will be essential to further increase the effectiveness, reliability, and scalability of IoT-based pest control systems in complex agricultural environments.

3.5 Implications for Smart and Sustainable Agriculture

The findings of this research have important implications for the advancement of smart and sustainable agriculture, particularly in the context of pest management. The integration of IoT-based monitoring with adaptive ultrasonic frequency control contributes directly to precision agriculture by enabling site-specific, data-driven pest control strategies. Rather than applying uniform and reactive control measures across entire fields, the proposed system allows targeted activation based on real-time detection of rat activity and environmental conditions. This level of precision improves control effectiveness while optimizing resource use, aligning pest management practices with the broader goals of precision farming.

From an environmental perspective, the proposed system offers significant benefits by reducing dependence on chemical rodenticides. Conventional chemical-based pest control methods often pose risks to soil quality, water resources, non-target organisms, and human health(Abrol & Shankar, 2014). By providing an effective non-chemical alternative, the adaptive ultrasonic system helps minimize ecological disruption and supports environmentally responsible farming practices. Reduced chemical use also lowers the risk of pest resistance and promotes a safer agricultural ecosystem, contributing to long-term sustainability.

The IoT-based architecture of the system enhances its scalability for large agricultural areas(Ahmed et al., 2018). Wireless communication and centralized monitoring enable multiple sensor and actuator nodes to be deployed across extensive fields without proportionally increasing labor requirements. Farmers and agricultural managers can oversee system performance remotely through a single platform, making it feasible to implement the technology in both smallholder farms and large-scale agricultural operations. This scalability is particularly valuable in regions with limited human resources for field monitoring and pest control.

Moreover, the proposed system has strong potential for integration with broader smart farming ecosystems. The collected pest activity and environmental data can be combined with other agricultural data streams, such as soil moisture, crop health indices, weather forecasts, and irrigation management systems. Such integration enables holistic farm management and supports predictive analytics for pest risk assessment and decision-making. By functioning as a modular component within a larger smart farming framework, the IoT-enabled adaptive ultrasonic pest control system contributes to the development of resilient, efficient, and sustainable agricultural systems capable of meeting future food production challenges.

3.6 Limitations and Future Work

Despite the promising results obtained in this study, several limitations must be acknowledged to provide a balanced and transparent assessment of the proposed IoT-based adaptive ultrasonic pest control system. One of the primary constraints relates to field size and spatial coverage(Hameed et al., 2013). The system was tested within a limited agricultural area, which may not fully represent the complexity and heterogeneity of larger rice fields. Variations in terrain, vegetation density, and field layout can influence ultrasonic wave propagation and sensor performance. In addition, seasonal variation poses a significant challenge, as changes in crop growth stages, weather patterns, and water levels in rice fields may affect rat behavior and system effectiveness. The study duration did not encompass all planting and harvesting seasons, limiting the ability to assess long-term performance across different agricultural cycles.

Another important limitation concerns the adaptive behavior of rats. Although adaptive ultrasonic frequency control reduced habituation compared to fixed-frequency systems, some level of behavioral adjustment was still observed over time(Wotjak, 2019). Rats demonstrated the ability to alter movement patterns or exploit areas with weaker ultrasonic coverage, indicating that ultrasonic deterrence alone may not completely eliminate pest presence in open-field environments. This highlights the need to consider integrated pest management strategies that combine ultrasonic control with complementary non-chemical approaches.

From a technical perspective, the system faced limitations related to network coverage and communication reliability. In remote agricultural areas, intermittent connectivity affected real-time data transmission and centralized monitoring. While local autonomous operation mitigated short-term disruptions, extended communication failures reduced the benefits of IoT-based monitoring. Additionally, sensor accuracy and durability were influenced by environmental factors such as heavy rainfall, high humidity, and temperature fluctuations, occasionally resulting in false detections or reduced sensitivity. These issues underscore the need for more robust, weather-resistant sensors and improved calibration mechanisms for long-term field deployment.

Future research should focus on several enhancements to address these limitations(Morgado et al., 2017). The incorporation of artificial intelligence (AI) and machine learning techniques could enable predictive modeling of rat activity based on historical and environmental data, allowing proactive rather than reactive control strategies. Improvements in energy management, such as more efficient solar power systems and hybrid energy storage solutions, would enhance system reliability and operational continuity in variable weather conditions. Furthermore, expanding the system to support multi-pest control by integrating additional sensors and control modalities could broaden its applicability beyond field rats. By addressing these technical and behavioral challenges, future work can further improve the effectiveness, scalability, and sustainability of IoT-enabled pest control systems within smart agriculture frameworks.

4. CONCLUSION

This research has demonstrated that the integration of Internet of Things (IoT) technology with adaptive ultrasonic frequency control represents a meaningful advancement in field rat pest management for agricultural environments. The key contribution of this study lies in the development and evaluation of an intelligent pest control system that combines real-time monitoring, data-driven decision-making, and adaptive actuation. By addressing the limitations of conventional fixed-frequency ultrasonic devices, the proposed system offers a more responsive and effective approach to reducing rat activity in rice fields while minimizing habituation effects. From a scientific perspective, this research contributes to the growing body of knowledge in smart agriculture and pest management by providing empirical evidence on the effectiveness of adaptive ultrasonic control supported by IoT-based sensing and communication. The study highlights the importance of integrating behavioral understanding, environmental data, and adaptive control mechanisms in designing sustainable pest management solutions. Methodologically, it demonstrates how IoT architectures can be applied in real-field conditions to support autonomous, scalable, and energy-efficient agricultural systems. In practical terms, the proposed system offers a viable and environmentally friendly alternative to chemical rodenticides, supporting safer farming practices and ecological sustainability. Its ability to operate autonomously, reduce labor requirements, and adapt to dynamic field conditions makes it suitable for real-world agricultural applications. With further refinement and integration into broader smart farming platforms, the system has strong potential for adoption by farmers and agricultural stakeholders seeking sustainable and precision-based pest control solutions. Overall, this research underscores the role of intelligent, IoT-enabled technologies in enhancing agricultural productivity and resilience while aligning with the principles of sustainable development.

REFERENCES

Abrol, D. P., & Shankar, U. (2014). Pesticides, food safety and integrated pest management. In *Integrated Pest Management: Pesticide Problems, Vol. 3* (pp. 167–199). Springer.

Ahmed, N., De, D., & Hussain, I. (2018). Internet of Things (IoT) for smart precision agriculture and farming in rural areas. *IEEE Internet of Things Journal*, *5*(6), 4890–4899.

Alam, M. S., & Arefifar, S. A. (2019). Energy management in power distribution systems: Review, classification, limitations and challenges. *IEEE Access*, *7*, 92979–93001.

Barnard, Y., Fischer, F., & Flament, M. (2015). Field operational tests and deployment plans. In *Vehicular ad*

hoc Networks: Standards, Solutions, and Research (pp. 393–408). Springer.
Chiesa, V., & Frattini, F. (2009). Evaluation and performance measurement of research and development: techniques and perspectives for multi-level analysis. In *Evaluation and Performance Measurement of Research and Development*. Edward Elgar Publishing.
Diaz, R. A. C., Ghita, M., Copot, D., Birs, I. R., Muresan, C., & Ionescu, C. (2020). Context aware control systems: An engineering applications perspective. *IEEE Access*, *8*, 215550–215569.
Du, P., Liu, Y., Chen, W., Zhang, S., & Deng, J. (2021). Fast and precise control for the vibration amplitude of an ultrasonic transducer based on fuzzy PID control. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, *68*(8), 2766–2774.
Elijah, O., Rahman, T. A., Orikumhi, I., Leow, C. Y., & Hindia, M. H. D. N. (2018). An overview of Internet of Things (IoT) and data analytics in agriculture: Benefits and challenges. *IEEE Internet of Things Journal*, *5*(5), 3758–3773.
Hameed, I. A., Bochtis, D., & Sørensen, C. A. (2013). An optimized field coverage planning approach for navigation of agricultural robots in fields involving obstacle areas. *International Journal of Advanced Robotic Systems*, *10*(5), 231.
Kalimuthu, K., Tseng, L.-C., Murugan, K., Panneerselvam, C., Aziz, A. T., Benelli, G., & Hwang, J.-S. (2020). Ultrasonic technology applied against mosquito larvae. *Applied Sciences*, *10*(10), 3546.
Macdonald, A., Hawkes, L. A., & Corrigan, D. K. (2021). Recent advances in biomedical, biosensor and clinical measurement devices for use in humans and the potential application of these technologies for the study of physiology and disease in wild animals. *Philosophical Transactions of the Royal Society B*, *376*(1831), 20200228.
Morgado, F. F. R., Meireles, J. F. F., Neves, C. M., Amaral, A., & Ferreira, M. E. C. (2017). Scale development: ten main limitations and recommendations to improve future research practices. *Psicologia: Reflexão e Crítica*, *30*.
Oosthuizen, M. K., & Bennett, N. C. (2015). The effect of ambient temperature on locomotor activity patterns in reproductive and non-reproductive female D amaraland mole-rats. *Journal of Zoology*, *297*(1), 1–8.
Page, A., Hijazi, S., Askan, D., Kantarci, B., & Soyata, T. (2016). Research directions in cloud-based decision support systems for health monitoring using Internet-of-Things driven data acquisition. *Int. J. Serv. Comput*, *4*(4), 18–34.
Pellegrino, R., Sinding, C., De Wijk, R. A., & Hummel, T. (2017). Habituation and adaptation to odors in humans. *Physiology & Behavior*, *177*, 13–19.
Potamitis, I., Eliopoulos, P., & Rigakis, I. (2017). Automated remote insect surveillance at a global scale and the internet of things. *Robotics*, *6*(3), 19.
Sifakis, J. (2018). System Design in the Era of IoT---Meeting the Autonomy Challenge. *ArXiv Preprint ArXiv:1806.09846*.
Singleton, G. (2003). *Impacts of rodents on rice production in Asia*.
Smith, R. H., & Meyer, A. N. (2015). Rodent control methods: non-chemical and non-lethal chemical, with special reference to food stores. *Rodent Pests and Their Control*, *2*, 81–101.
Talwar, S. K., & Gerstein, G. L. (2001). Reorganization in awake rat auditory cortex by local microstimulation and its effect on frequency-discrimination behavior. *Journal of Neurophysiology*, *86*(4), 1555–1572.
Tejedor, J., Macias-Guarasa, J., Martins, H. F., Pastor-Graells, J., Martin-Lopez, S., Guillén, P. C., De Pauw, G., De Smet, F., Postvoll, W., & Ahlen, C. H. (2018). Real field deployment of a smart fiber-optic surveillance system for pipeline integrity threat detection: Architectural issues and blind field test results. *Journal of Lightwave Technology*, *36*(4), 1052–1062.
Telaumbanua, M., & Waluyo, S. (2018). Control system design for rat pest repellent in the rice field using a modified ATMega328 microcontroller modified with ultrasonic sound wave. *International Journal of Engineering Inventions*, *7*(8), 22–28.
Tumer, I., & Smidts, C. (2010). Integrated design-stage failure analysis of software-driven hardware systems. *IEEE Transactions on Computers*, *60*(8), 1072–1084.
Vorobyov, V., Janać, B., Pešić, V., & Prolić, Z. (2010). Repeated exposure to low-level extremely low frequency-modulated microwaves affects cortex-hypothalamus interplay in freely moving rats: EEG study. *International Journal of Radiation Biology*, *86*(5), 376–383.
Wotjak, C. T. (2019). Sound check, stage design and screen plot–how to increase the comparability of fear conditioning and fear extinction experiments. *Psychopharmacology*, *236*(1), 33–48.