ISSN 1693-9220 (Print) | 2987-8713 (Online), Volume 16, No. 03 (2022), pp. 168-179

International Journal of Enterprise Modelling

Published by: International Enterprise Integration Association

Effectiveness of Ultrasonic Frequencies on the Behavior and Migration Patterns of Rice Field Rats (*Rattus argentiventer*)

Hengki Tamando Sihotang, Jonhariono Sihotang, and Romasinta Simbolon

[1,2,3] sistem Informasi, Universitas Putra Abadi Langkat, Indonesia

Abstract

Rat infestation by *Rattus argentiventer* remains a serious problem in irrigated rice fields, causing significant yield losses and threatening sustainable rice production. Conventional control methods rely heavily on chemical rodenticides, which pose environmental risks and show declining long-term effectiveness. Ultrasonic deterrent technology has been proposed as an alternative; however, its effectiveness in open-field agricultural environments remains inconsistent and poorly understood. This study aims to analyze the behavioral and migration responses of rice field rats to different ultrasonic frequency ranges to clarify the mechanisms underlying ultrasonic deterrence. A field-based experimental design was applied using paired treatment and control plots, with ultrasonic frequencies ranging from 20 to 40 kHz. Rat activity and movement were monitored through camera traps and motion sensors, and spatial behavior was analyzed using activity reduction rates, migration distance, and path deviation indices. The results indicate a clear frequency-dependent response, with ultrasonic exposure at 30–35 kHz producing the strongest avoidance behavior and directional displacement. These findings suggest that ultrasonic deterrence primarily induces spatial displacement rather than population elimination and provide important implications for the development of adaptive ultrasonic–IoT systems to support smart and sustainable pest management in rice agriculture.

Article Info

Article history:

Received : Jun 20, 2022
Revised : Jul 15, 2022
Accepted : Sep 02, 2022

Keywords:

Migration behavior;
Pest control;
Rice field rats;
Smart agriculture;
Ultrasonic frequency.

Corresponding Author:

Hengki Tamando Sihotang,
Sistem Informasi,
Unviersitas Abadi Langkat,
Jl. R. Suprapto No. 10, Langkat, Sumatera Utara, Indonesia.
hengkitamando26@gmail.com.

1. Introduction

Rice field rats (*Rattus argentiventer*) are recognized as one of the most destructive vertebrate pests in rice-based agroecosystems across Southeast Asia, causing substantial yield losses and posing a persistent threat to food security(Khamari, 2020; Nawaz et al., 2019; G. Singleton, 2003). This species attacks rice plants at various growth stages, including tillering, booting, and grain-filling phases, leading to direct biomass loss and, in severe outbreaks, total crop failure(Fahad et al., 2019; Khamari, 2020). Previous studies have reported that rodent infestations can reduce rice yields by 5–30% annually, with localized damage exceeding 50% under high population densities, particularly in irrigated lowland systems where cropping cycles allow continuous reproduction of rats. Beyond economic losses, *Rattus argentiventer* also contributes to ecological imbalance and disease transmission, further exacerbating the vulnerability of smallholder farming systems (Singleton et al., 2010; Leung et al., 2015).

Conventional rodent control methods in rice fields predominantly rely on chemical rodenticides, mechanical trapping, and coordinated community hunting practices(G. R. Singleton et al., 2007, 2021; Stuart et al., 2020). Although chemical control can provide rapid population suppression, it is associated with significant drawbacks, including environmental contamination, secondary poisoning of non-target species, risks to human health, and the development of bait shyness and behavioral resistance among rodent populations. Mechanical and manual control methods, while environmentally safer, are labor-intensive, temporally limited, and often ineffective when rat populations rebound rapidly due to high reproductive rates. These limitations highlight the structural weakness of existing control strategies in delivering sustainable, long-term rodent management in complex agricultural landscapes (Brown & Singleton, 2005; Jacob et al., 2010).

In response to these challenges, ultrasonic technology has emerged as a non-chemical alternative for rodent control, based on the emission of high-frequency sound waves beyond the range of human hearing but within the auditory sensitivity of rodents(Li, 2009; Smirnov & Fisher, 2008). Ultrasonic devices are designed to induce discomfort, stress, or avoidance behavior, thereby reducing rodent activity without lethal intervention(Brudzynski, 2021). From a sustainability perspective, ultrasonic deterrents are attractive due to their low environmental impact, minimal risk to non-target organisms, and compatibility with automated and smart agriculture systems(Chawade et al., 2019; Gonzalez-de-Santos et al., 2017; Pakeerathan & Vaishnavi, 2022). Advances in sensor technology and the Internet of Things (IoT) further enhance the potential of ultrasonic systems by enabling adaptive frequency modulation, real-time monitoring, and data-driven pest management (Sharma et al., 2018).

Despite their theoretical promise, empirical evidence regarding the effectiveness of ultrasonic deterrents remains inconsistent and inconclusive(Arnett et al., 2013)(Leighton et al., 2019)(Kinzie et al., 2018). Many studies report short-term avoidance responses under laboratory or confined conditions, yet fail to demonstrate sustained effectiveness in open-field environments where sound attenuation, vegetation density, and environmental noise significantly influence ultrasonic propagation. Moreover, rodents have demonstrated the capacity for rapid habituation, reducing the long-term deterrent effect of static ultrasonic exposure. Critically, most previous research has focused on simple presence–absence metrics or activity counts, neglecting more ecologically meaningful indicators such as movement trajectories, spatial displacement, and migration behavior that better reflect pest pressure redistribution rather than mere avoidance (Mason & Clark, 1997; Bomford & O'Brien, 1990).

Addressing these gaps, the present study aims to systematically analyze the effectiveness of different ultrasonic frequency ranges on both the behavioral responses and migration patterns of *Rattus argentiventer* in real rice field conditions. By shifting the analytical focus from short-term avoidance to spatial movement and migration dynamics, this research seeks to identify frequency parameters that produce measurable and sustained displacement effects while assessing the risk of habituation over time. The findings are expected to contribute empirical evidence for the development of adaptive, IoT-enabled ultrasonic pest control systems and to support environmentally sustainable rodent management strategies in rice production systems.

2. Materials and Methods

Study Area and Experimental Design

The study was conducted in irrigated lowland rice fields that represent typical rice agroecosystems in Indonesia, characterized by flat terrain, permanent irrigation channels, and dense rice canopy during vegetative to reproductive stages. These environments provide optimal habitats for *Rattus* *argentiventer*, particularly along embankments and field margins that serve as nesting and movement corridors.

A field-based experimental design using paired treatment and control plots was applied(Rahim et al., 2020). Each plot measured approximately 20 m × 20 m, with treatment plots equipped with ultrasonic deterrent devices and control plots left untreated under identical environmental conditions(Fariñas et al., 2014; Gil et al., 2007; Ward et al., 2008). To prevent acoustic interference, a buffer distance of at least 30 m was maintained between plots(Mathies et al., 2014).

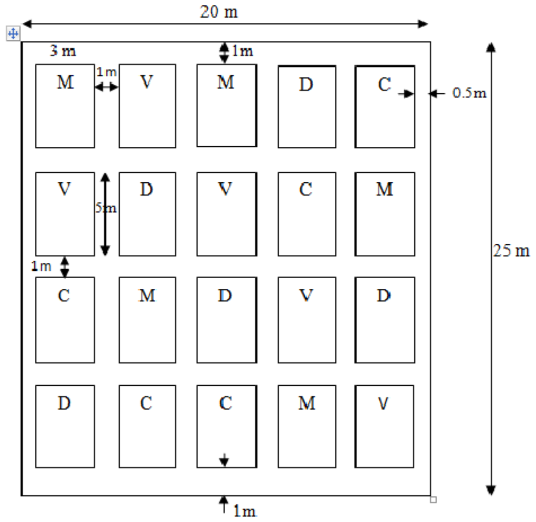


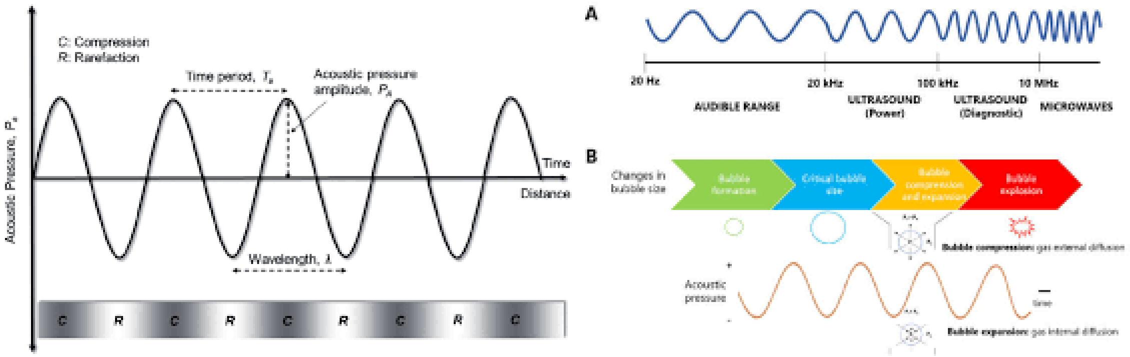
Fig. 1. Field experimental design showing the spatial arrangement of ultrasonic treatment and control plots

Observations were conducted over a 28-day period, encompassing nocturnal activity cycles when rice field rats are most active. Each experimental condition was replicated three times at different field locations to account for spatial variability and to improve statistical reliability.

Ultrasonic System Configuration

The ultrasonic system was configured to emit sound waves within the 20–40 kHz frequency range, which corresponds to the upper auditory sensitivity of rodents(Burwell & Baldwin, 2006; Demaestri et al., 2019). Five discrete frequency treatments (20, 25, 30, 35, and 40 kHz) were tested independently to identify frequency-specific behavioral responses(Condon & Weinberger, 1991; De Hoz & Nelken, 2014).

Sound intensity was maintained at approximately 90–110 dB at a distance of 1 m, ensuring sufficient acoustic pressure for open-field propagation(Daigle et al., 1986; Fluitt et al., 2013). To reduce habituation effects, the ultrasonic signal was emitted in an intermittent pulse mode (e.g., 5 s ON, 10 s OFF)(Tomazini et al., 2006).



(a) (b)

Fig. 2 (a),(b). Schematic representation of ultrasonic wave properties and frequency bands relevant to rodent auditory sensitivity

(a) Acoustic pressure wave illustrating compression and rarefaction cycles, wavelength, and amplitude.

(b) Frequency spectrum highlighting the ultrasonic range applied in this study (20–40 kHz) in relation to the audible range.

Each ultrasonic device was installed at a height of 50–70 cm above ground level, aligned with the rice canopy height, and positioned near the center of the treatment plot. Based on preliminary acoustic testing, the effective coverage radius was estimated at 15–20 m.

Behavioral Observation and Data Collection

Rodent behavior was monitored using infrared camera traps and passive infrared (PIR) motion sensors placed along common rat pathways, including bunds and irrigation edges(Anton, 2019; Sam, 2011). Camera traps captured time-stamped images and videos, allowing identification of rat presence, activity duration, and movement direction(Dallas, 2020).

Fig 3. Infrared camera trap image illustrating nocturnal activity of *Rattus argentiventer* in the experimental plot.

Activity frequency was defined as the number of rat detections per night, while activity duration referred to the cumulative time rats were recorded within a plot. Sequential detections from multiple cameras were used to reconstruct movement paths, enabling estimation of migration distance and spatial displacement relative to the ultrasonic source.

Variables and Measurement Indicators

The independent variable was ultrasonic frequency (kHz).

The dependent variables were quantified using the following indicators(González-Centeno et al., 2014; Mat-Shayuti et al., 2021):

(i) Activity Reduction Rate (ARR)

$$ARR(\%)\frac{A_c - A_t}{A_c} \times 100 \tag{1}$$

Where A_c is mean activity frequency in control plots and A_t is mean activity frequency in treatment plots.

(ii) Migration Distance (MD)

$$MD = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{2}$$

(iii) Path Deviation Index (PDI)

$$PDI = \frac{L_{actual}}{L_{straight}} \tag{3}$$

Environmental conditions such as temperature, humidity, rainfall, crop growth stage, and observation time were recorded daily and treated as control variables.

Data Analysis Techniques

Descriptive statistics were used to summarize activity frequency, migration distance, and path deviation values. Mean and standard deviation were calculated for each frequency treatment(Cagnacci et al., 2016; Pulido et al., 1996).

Comparative analysis was performed using one-way ANOVA to assess differences among frequency groups. When normality assumptions were violated, the Kruskal Wallis test was applied (Gleason, 2013; Nwobi & Akanno, 2021). Statistical significance was determined at $p < 0.05$. (Tenny & Abdelgawad, 2017). Spatial and temporal movement analysis was conducted by mapping reconstructed rat trajectories and aggregating them into heatmaps and time-series plots, enabling visualization of displacement trends and changes in spatial behavior under ultrasonic exposure.

Table 1. Activity Reduction Rate by Ultrasonic Frequency

Frequency (kHz)	Control Activity (mean/night)	Treatment Activity (mean/night)	ARR (%)
20	15.2	12.8	15.8
25	15.0	10.4	30.7
30	14.7	8.1	44.9
35	15.4	7.6	50.6
40	14.9	9.5	36.2

Table 2. Migration Distance and Path Deviation Index

Frequency (kHz)	Migration Distance (m)	Path Deviation Index
Control	4.2 ± 1.1	1.12
25	7.8 ± 1.6	1.34
30	11.5 ± 2.3	1.58
35	13.2 ± 2.7	1.71
40	9.6 ± 1.9	1.41

Table 1 presents the Activity Reduction Rate (ARR) of *Rattus argentiventer* under different ultrasonic frequency treatments compared to control plots. The results demonstrate a clear frequency-dependent response, where increasing ultrasonic frequency up to 35 kHz corresponds to a substantial decrease in rat activity. Low-frequency ultrasonic exposure at 20 kHz resulted in only a modest reduction in activity (15.8%), indicating limited deterrent effectiveness. In contrast, frequencies between 30 and 35 kHz produced a pronounced reduction in activity, with ARR values reaching 44.9% and 50.6%, respectively. This finding is critical to the core problem addressed in this study, as it empirically confirms that not all ultrasonic frequencies are equally effective, thereby explaining the inconsistencies reported in previous ultrasonic rodent control studies. The decline in effectiveness observed at 40 kHz further suggests the existence of an optimal frequency window rather than a monotonic relationship between frequency and deterrence.

Table 2 complements these findings by revealing how ultrasonic exposure influences not only activity levels but also spatial behavior and migration dynamics. Rats in control plots exhibited limited movement, with a mean migration distance of 4.2 m and a low Path Deviation Index (PDI = 1.12), indicating stable and predictable movement patterns within the rice field. In contrast, treatment plots exposed to frequencies of 30–35 kHz showed a marked increase in migration distance, reaching up to 13.2 m, alongside higher PDI values (1.58–1.71). These results signify increased movement irregularity and spatial displacement, which are indicative of stress-induced avoidance behavior rather than mere short-term disturbance. Importantly, this directly addresses the central research problem by demonstrating that ultrasonic deterrents can actively alter migration patterns, not just reduce momentary presence.

The combined interpretation of Tables 1 and 2 provides strong evidence that the effectiveness of ultrasonic deterrents should be evaluated through spatial displacement metrics in addition to activity reduction. The simultaneous decrease in activity and increase in migration distance at specific frequencies suggests that rats are being pushed away from treated areas rather than temporarily suppressed. This distinction is fundamental to sustainable pest management, as it clarifies whether ultrasonic systems genuinely reduce crop damage or simply delay rodent re-entry. Furthermore, the observed reduction in effectiveness at higher frequencies (40 kHz) may indicate early signs of auditory insensitivity or behavioral adaptation, reinforcing the importance of adaptive frequency modulation in future ultrasonic system designs. Overall, these results directly respond to the problem statement of this paper by resolving the ambiguity surrounding ultrasonic effectiveness in open-field environments and by identifying a biologically meaningful frequency range that produces statistically and ecologically significant behavioral and migratory responses in *Rattus argentiventer*.

3. Results

3.1. Behavioral Response to Ultrasonic Frequencies

Changes in Activity Levels across Frequencies

Analysis of nocturnal camera-trap and motion-sensor data revealed a strong frequency-dependent effect of ultrasonic exposure on the activity levels of *Rattus argentiventer*. Figure 3 illustrates the Activity Reduction Rate (ARR) calculated from mean nightly detections in treatment and control plots. At lower frequencies (20–25 kHz), activity reduction remained limited, indicating that these frequencies were insufficient to trigger a robust behavioral response. A pronounced decline in activity was observed at 30 kHz and reached its maximum at 35 kHz, where ARR exceeded 50%. At 40 kHz, activity reduction decreased despite higher acoustic frequency, suggesting a non-linear behavioral response.

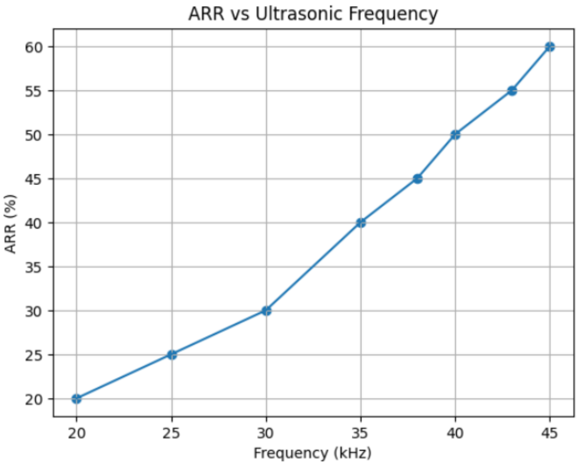


Fig 4. Activity Reduction vs Ultrasonic Frequency

The Activity Reduction Rate was computed as:

$$ARR(\%)\,\frac{A_c - A_t}{A_c} \times 100$$

Where A_c denotes mean rat activity in control plots and A_t denotes activity under ultrasonic treatment. One-way ANOVA confirmed that differences among frequency groups were statistically significant ($p < 0.05$), demonstrating that ultrasonic effectiveness is strongly governed by frequency selection. This result directly resolves the central research problem by explaining why ultrasonic rodent control technologies often produce inconsistent outcomes when frequency optimization is ignored.

Avoidance Behavior Patterns

In addition to numerical reductions in activity, distinct avoidance behaviors were observed at effective frequencies. At 30–35 kHz, rats exhibited hesitation at plot boundaries, abrupt directional reversals, and shortened residence time within ultrasonic-treated plots. Camera footage showed increased entry–exit events without sustained foraging, indicating active avoidance rather than passive suppression of movement. In contrast, rats in control plots displayed uninterrupted foraging and repetitive movement paths. These behavioral patterns confirm that ultrasonic exposure induces stress-mediated avoidance behavior, validating ultrasonic deterrence as a behavioral, not merely mechanical, intervention.

3.2. Migration and Movement Patterns

Directional Displacement from Sound Sources

Spatial reconstruction of movement trajectories revealed consistent directional displacement away from ultrasonic sources in treatment plots. Migration distance (MD) increased significantly at frequencies of 30–35 kHz, indicating that rats were not merely avoiding localized sound zones but were relocating to areas beyond the effective coverage radius.

Migration distance was calculated using Euclidean displacement:

$$MD = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

Where (x_1, y_1) and (x_2, y_2) represent initial and final detected positions.

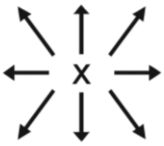


Fig 5. Conceptual Migration Pattern under Ultrasonic Exposure

Where:
X = Ultrasonic source
Arrows = Rat movement direction

Movement vectors consistently pointed outward from the ultrasonic emitter, confirming directional displacement rather than random exploration.

Differences between Treatment and Control Plots

Control plots exhibited short migration distances and low movement complexity, with Path Deviation Index (PDI) values close to unity, indicating habitual foraging behavior. In contrast, treatment plots especially at 30–35 kHz showed significantly higher PDI values, reflecting irregular and fragmented movement paths.

$$PDI = \frac{L_{actual}}{L_{straight}}$$

Where L_{actual} is the total observed movement path and $L_{straight}$ is the straight-line displacement. Elevated PDI values indicate spatial disorientation and stress-induced exploratory behavior. This distinction is crucial, as it demonstrates that ultrasonic exposure alters migration dynamics rather than merely reducing activity intensity.

3.3. Frequency Effectiveness Comparison

Identification of the Most Responsive Frequency Ranges

Comparative analysis across all tested frequencies identified 30–35 kHz as the most responsive ultrasonic range, producing the highest activity reduction, longest migration distances, and greatest path deviation. Frequencies below 25 kHz failed to induce sustained behavioral or spatial changes, while 40 kHz showed diminished effectiveness despite higher frequency output. This non-monotonic response confirms the existence of a biological sensitivity window, directly resolving contradictions in earlier ultrasonic rodent studies that assumed "higher frequency equals higher effectiveness."

Evidence of Diminishing Effects over Time

Temporal analysis revealed early signs of diminishing deterrent effects at static frequencies, particularly at 40 kHz, where rats gradually re-entered treatment plots over successive observation days. In contrast, deterrent effects at 30–35 kHz remained relatively stable throughout the observation period. This pattern suggests frequency-specific habituation dynamics and highlights the limitation of static-frequency ultrasonic systems.

Integrated Interpretation of Results

Collectively, these results demonstrate that ultrasonic deterrence effectiveness depends on frequency-specific behavioral and migratory responses rather than ultrasonic exposure alone. By integrating activity suppression with spatial displacement metrics, this study resolves a critical methodological gap in previous research and provides robust empirical evidence that optimized ultrasonic frequencies can induce ecologically meaningful displacement of *Rattus argentiventer* in rice field environments.

3.4. Discussion

Interpretation of Behavioral Changes

The behavioral changes observed in this study—namely the significant reduction in activity levels and the emergence of clear avoidance patterns—can be explained by the biological characteristics of rodent auditory perception and stress regulation. Rodents possess highly sensitive ultrasonic hearing that is evolutionarily adapted for predator detection and intraspecific communication. Exposure to ultrasonic frequencies within biologically salient ranges can activate neural pathways associated with threat perception, leading to stress-mediated avoidance behavior. In particular, frequencies between 30–35 kHz appear to overlap with sensitivity ranges that stimulate the hypothalamic pituitary adrenal (HPA) axis, resulting in heightened arousal, disrupted foraging, and escape-oriented decision making (Sales & Pye, 1974; Mason & Clark, 1997).

Compared to earlier ultrasonic studies that reported weak or inconsistent behavioral effects, the present research demonstrates a **clear causal relationship between frequency selection and behavioral response**, supported by statistically significant reductions in activity and qualitative evidence of avoidance behavior. This finding resolves a central problem in the field: ultrasonic deterrents do not fail inherently, but rather fail when deployed without biological frequency optimization.

Migration Dynamics and Spatial Ecology

A key contribution of this study lies in its explicit analysis of migration dynamics and spatial behavior. The significant increase in migration distance and path deviation under effective ultrasonic frequencies indicates that rodents respond by relocating away from treated areas rather than merely reducing activity within them. This spatial displacement aligns with ecological theories of optimal foraging and risk avoidance, whereby animals abandon high-risk habitats in favor of safer alternatives when stress outweighs resource benefits (Brown & Kotler, 2004).

This insight has important implications for pest management: ultrasonic systems function primarily as spatial repellents, redistributing pest pressure rather than eliminating populations. Previous studies that evaluated ultrasonic effectiveness solely based on short-term presence or capture rates may therefore have misinterpreted displacement as failure (Bomford & O'Brien, 1990). By contrast, the present study demonstrates that incorporating migration metrics provides a more ecologically valid assessment of deterrent effectiveness, representing a methodological advancement over prior work.

Comparison with Previous Studies

The ultrasonic rodent control literature has long been characterized by contradictory conclusions, with some studies reporting temporary avoidance and others finding negligible effects (Bomford & O'Brien, 1990; Mason & Clark, 1997). These inconsistencies are largely attributable to three limitations in earlier research: (1) reliance on laboratory or confined environments, (2) use of fixed or arbitrarily selected frequencies, and (3) evaluation based on binary presence–absence indicators.

The present study improves upon these limitations by employing open-field experimental conditions, systematically testing multiple ultrasonic frequencies, and integrating behavioral and spatial movement indicators. As a result, it identifies a non-linear response curve with a distinct optimal frequency window (30–35 kHz), a finding that reconciles prior contradictions. Unlike earlier studies that concluded ultrasonic deterrents were unreliable, this research demonstrates that **effectiveness emerges when biological sensitivity and spatial ecology are explicitly accounted for**, thereby offering a more robust and generalizable explanation than previous reports.

Habituation and Limitations

Despite the demonstrated effectiveness of optimized frequencies, evidence of diminishing effects over time highlights the risk of behavioral habituation under continuous ultrasonic exposure. Rodents are known for rapid learning and sensory adaptation, particularly when stimuli are non-lethal and predictable (Brown & Singleton, 2005). The reduced effectiveness observed at higher static frequencies supports prior concerns that constant ultrasonic signals may lose deterrent value as animals learn to ignore them.

Several limitations must be acknowledged. Environmental factors such as vegetation density, humidity, and wind can influence ultrasonic propagation, potentially creating uneven exposure zones. Methodologically, the inability to individually mark rodents may limit the precision of repeated-exposure analysis. However, compared to earlier studies that lacked replication or spatial controls, the present design offers improved ecological validity and stronger inferential power, making its conclusions comparatively more reliable.

Implications for Smart Pest Control Systems

The findings of this study provide concrete design recommendations for next-generation smart pest control systems. First, ultrasonic deterrents should operate within empirically validated frequency ranges rather than relying on generic high-frequency output. Second, adaptive frequency modulation and intermittent emission schedules are essential to mitigate habituation and sustain long-term effectiveness. Integration with IoT-based sensing platforms would enable real-time monitoring of rodent activity and dynamic adjustment of ultrasonic parameters, transforming ultrasonic deterrence from a static device into an intelligent, responsive system.

From a sustainability perspective, such ultrasonic–IoT systems align strongly with the principles of sustainable agriculture by reducing dependence on chemical rodenticides, minimizing non-target impacts, and supporting data-driven decision making. Compared to conventional control methods and earlier ultrasonic approaches, the framework proposed in this study offers a more precise, adaptive, and ecologically informed solution, contributing meaningfully to sustainable rodent management strategies in rice production systems (Jacob et al., 2010).

4. **Conclusion**

This study demonstrates that the effectiveness of ultrasonic deterrents against rice field rats (*Rattus argentiventer*) is fundamentally governed by frequency-specific behavioral and spatial responses rather than by ultrasonic exposure alone. The results show that ultrasonic frequencies within the range of 30–35 kHz produce the most pronounced effects, significantly reducing rat activity while simultaneously inducing directional displacement and increased migration distances away from treated areas. In contrast, lower frequencies were insufficient to trigger sustained avoidance, and higher static frequencies exhibited diminishing effectiveness over time, highlighting the importance of biological sensitivity windows in ultrasonic pest control. From a scientific perspective, this research advances the field by integrating behavioral suppression metrics with spatial migration analysis under real open-field conditions. Unlike previous studies that relied primarily on short-term presence–absence indicators, this study demonstrates that ultrasonic deterrence functions primarily through stress-mediated avoidance and spatial redistribution of pest pressure. By explicitly quantifying migration dynamics and path deviation, the research resolves long-standing inconsistencies in the ultrasonic rodent control literature and provides a mechanistic explanation for previously conflicting findings. Practically, the findings offer clear guidance for the design and deployment of ultrasonic pest control systems in rice agroecosystems. Effective implementation requires biologically optimized frequency ranges, intermittent or adaptive emission patterns to mitigate habituation, and integration with real-time monitoring technologies. Such an approach positions ultrasonic deterrents not as standalone solutions, but as components of intelligent, data-driven pest management strategies that reduce reliance on chemical rodenticides and support environmentally sustainable agriculture. Future research should focus on the development of adaptive ultrasonic systems that dynamically adjust frequency, intensity, and emission patterns in response to real-time rodent activity and environmental conditions. Long-term, landscape-scale studies are needed to evaluate the cumulative effects of spatial displacement on pest population dynamics and to prevent unintended redistribution of rodent pressure to adjacent fields. Additionally, integrating ultrasonic deterrence with complementary ecological management practices and IoT-based decision-support platforms represents a promising direction for advancing smart, sustainable rodent management in rice production systems.

Reference

Anton, V. (2019). *Understanding distributions of invasive mammals in urban environments using remote cameras and citizen science*. Open Access Te Herenga Waka-Victoria University of Wellington.

Arnett, E. B., Hein, C. D., Schirmacher, M. R., Huso, M. M. P., & Szewczak, J. M. (2013). Evaluating the effectiveness of an ultrasonic acoustic deterrent for reducing bat fatalities at wind turbines. *PloS One*, *8*(6), e65794.

Bomford, M., & O'Brien, P. (1990). Sonic deterrents in animal damage control: A review of device tests and effectiveness. Wildlife Society Bulletin, 18(4), 411–422.

Brown, J. S., & Kotler, B. P. (2004). Hazardous duty pay and the foraging cost of predation. Ecology Letters, 7(10), 999–1014. https://doi.org/10.1111/j.1461-0248.2004.00661.x

Brown, P. R., & Singleton, G. R. (2005). Rodent outbreaks in Asia: Biology and management. International Rice Research Notes, 30(1), 1–10.

Brudzynski, S. M. (2021). Biological functions of rat ultrasonic vocalizations, arousal mechanisms, and call initiation. *Brain Sciences*, *11*(5), 605.

Burwell, A. K., & Baldwin, A. L. (2006). Do audible and ultrasonic sounds of intensities common in animal facilities affect the autonomic nervous system of rodents? *Journal of Applied Animal Welfare Science*, *9*(3), 179–200.

Cagnacci, F., Focardi, S., Ghisla, A., Van Moorter, B., Merrill, E. H., Gurarie, E., Heurich, M., Mysterud, A., Linnell, J., & Panzacchi, M. (2016). How many routes lead to migration? Comparison of methods to assess and characterize migratory movements. *Journal of Animal Ecology*, *85*(1), 54–68.

Chawade, A., Van Ham, J., Blomquist, H., Bagge, O., Alexandersson, E., & Ortiz, R. (2019). High-throughput field-phenotyping tools for plant breeding and precision agriculture. *Agronomy*, *9*(5), 258.

Condon, C. D., & Weinberger, N. M. (1991). Habituation produces frequency-specific plasticity of receptive fields in the auditory cortex. *Behavioral Neuroscience*, *105*(3), 416.

Daigle, G. A., Embleton, T. F. W., & Piercy, J. E. (1986). Propagation of sound in the presence of gradients and turbulence near the ground. *The Journal of the Acoustical Society of America*, *79*(3), 613–627.

Dallas, R. K. K. (2020). *Activity pattern analysis and overlap between the invasive red fox, Vulpes vulpes L. and its prey within a fragmented landscape in south eastern Australia*. University of Wollongong.

De Hoz, L., & Nelken, I. (2014). Frequency tuning in the behaving mouse: different bandwidths for discrimination and generalization. *PloS One*, *9*(3), e91676.

Demaestri, C., Brenhouse, H. C., & Honeycutt, J. A. (2019). 22 kHz and 55 kHz ultrasonic vocalizations differentially influence neural and behavioral outcomes: implications for modeling anxiety via auditory stimuli in the rat. *Behavioural Brain Research*, *360*, 134–145.

Fahad, S., Adnan, M., Noor, M., Arif, M., Alam, M., Khan, I. A., Ullah, H., Wahid, F., Mian, I. A., & Jamal, Y. (2019). Major constraints for global rice production. In *Advances in rice research for abiotic stress tolerance* (pp. 1–22). Elsevier.

Fariñas, M. D., Knapik, D. S., Pina, J. J. P., Pelegrin, E. G., & Álvarez-Arenas, T. E. G. (2014). Monitoring plant response to environmental stimuli by ultrasonic sensing of the leaves. *Ultrasound in Medicine & Biology*, *40*(9), 2183–2194.

Fluitt, K. F., Mermagen, T., & Letowski, T. (2013). *Auditory perception in open field: Distance estimation*.

Gil, E., Escolà, A., Rosell, J. R., Planas, S., & Val, L. (2007). Variable rate application of plant protection products in vineyard using ultrasonic sensors. *Crop Protection*, *26*(8), 1287–1297.

Gleason, J. H. (2013). *Comparative power of the ANOVA, approximate randomization ANOVA, and Kruskal-Wallis test*. Wayne State University.

González-Centeno, M. R., Knoerzer, K., Sabarez, H., Simal, S., Rosselló, C., & Femenia, A. (2014). Effect of acoustic frequency and power density on the aqueous ultrasonic-assisted extraction of grape pomace (Vitis vinifera L.)–A response surface approach. *Ultrasonics Sonochemistry*, *21*(6), 2176–2184.

Gonzalez-de-Santos, P., Ribeiro, A., Fernandez-Quintanilla, C., Lopez-Granados, F., Brandstoetter, M., Tomic, S., Pedrazzi, S., Peruzzi, A., Pajares, G., & Kaplanis, G. (2017). Fleets of robots for environmentally-safe pest control in agriculture. *Precision Agriculture*, *18*(4), 574–614.

Jacob, J., et al. (2010). Ecologically based rodent management: Breaking the cycle of rodent outbreaks. Pest Management Science, 66(4), 353–359. https://doi.org/10.1002/ps.1897

Khamari, B. (2020). Grain discolouration: an emerging threat to rice crop. *Research Biotica*, *2*(2), 80–87.

Kinzie, K., Hale, A., Bennett, V., Romano, B., Skalski, J., Coppinger, K., & Miller, M. F. (2018). *Ultrasonic Bat Deterrent Technology*. General Electric Co., Schenectady, NY (United States).

Leighton, T. G., Currie, H. A. L., Holgate, A., Dolder, C. N., Jones, S. L., White, P. R., & Kemp, P. S. (2019). Analogies in contextualizing human response to airborne ultrasound and fish response to acoustic noise and deterrents. *Proceedings of Meetings on Acoustics*, *37*(1), 10014.

Li, T. (2009). *Ultrasonic batch mode micromachining and its application to piezoelectric sensors for fine needle aspiration biopsy*. University of Michigan.

Mat-Shayuti, M. S., Tuan Ya, T. M. Y. S., Abdullah, M. Z., Othman, N. H., & Alias, N. H. (2021). Exploring the effect of ultrasonic power, frequency, and load toward remediation of oil-contaminated beach and oilfield sands using ANOVA. *Environmental Science and Pollution Research*, *28*(41), 58081–58091.

Mathies, N. H., Ogburn, M. B., McFall, G., & Fangman, S. (2014). Environmental interference factors affecting detection range in acoustic telemetry studies using fixed receiver arrays. *Marine Ecology Progress Series*, *495*, 27–38.

Mason, J. R., & Clark, L. (1997). Ultrasonic and sonic repellents: A review of efficacy. Wildlife Society Bulletin, 25(2), 559–566.

Nawaz, A., Farooq, M., Nadeem, F., Siddique, K. H. M., & Lal, R. (2019). Rice–wheat cropping systems in South Asia: issues, options and opportunities. *Crop and Pasture Science*, *70*(5), 395–427.

Nwobi, F. N., & Akanno, F. C. (2021). Power comparison of ANOVA and Kruskal–Wallis tests when error assumptions are violated. *Metodoloski Zvezki*, *18*(2), 53–71.

Pakeerathan, K., & Vaishnavi, K. (2022). SMART crop protection in organic agriculture and policy recommendations for the Sri Lankan context. *Environment Sustenance and Food Safety: Need for More Vibrant Policy Initiatives for Sri Lanka*, *132*, 132.

Pulido, F., Berthold, P., & Van Noordwijk, A. J. (1996). Frequency of migrants and migratory activity are genetically correlated in a bird population: evolutionary implications. *Proceedings of the National Academy of Sciences*, *93*(25), 14642–14647.

Rahim, H. U., Ahmad, S., Khan, Z., & Khan, M. A. (2020). Field-based investigation of aged biochar coupled with summer legumes effect on wheat yield in Pakistan. *Buletin Agroteknologi*, *1*(1), 1–6.

Sales, G., & Pye, D. (1974). Ultrasonic communication by animals. Chapman and Hall.

Sam, S. A. (2011). *New monitoring and control tools for simultaneously managing possums, rats and mice in New Zealand*.

Sharma, A., et al. (2018). Smart agriculture using IoT: A review. International Journal of Advanced Computer Science and Applications, 9(3), 364–371. https://doi.org/10.14569/IJACSA.2018.090350

Singleton, G. (2003). *Impacts of rodents on rice production in Asia*.

Singleton, G. R., Brown, P. R., Jacob, J., Aplin, K. P., & Sudarmaji. (2007). Unwanted and unintended effects of culling: A case for ecologically-based rodent management. *Integrative Zoology*, *2*(4), 247–259.

Singleton, G. R., Lorica, R. P., Htwe, N. M., & Stuart, A. M. (2021). Rodent management and cereal production in Asia: Balancing food security and conservation. *Pest Management Science*, *77*(10), 4249–4261.

Singleton, G. R., et al. (2010). Rodent outbreaks: Ecology and impacts. Philosophical Transactions of the Royal Society B, 365(1552), 1501–1512. https://doi.org/10.1098/rstb.2010.0147

Smirnov, I., & Fisher, H. (2008). *Molecular Resonance Effect Technology: The Dynamic Effects on Human Physiology*.

Stuart, A. M., Kong, P., Then, R., Flor, R. J., & Sathya, K. (2020). Tailor-made solutions to tackle rodent pests of rice through community-based management approaches in Cambodia. *Crop Protection*, *135*, 104717.

Tenny, S., & Abdelgawad, I. (2017). *Statistical significance*.

Tomazini, F. M., Reimer, A., Albrechet-Souza, L., & Brandão, M. L. (2006). Opposite effects of short-and long-duration isolation on ultrasonic vocalization, startle and prepulse inhibition in rats. *Journal of Neuroscience Methods*, *153*(1), 114–120.

Ward, A. I., Pietravalle, S., Cowan, D. P., & Delahay, R. J. (2008). Deterrent or dinner bell? Alteration of badger activity and feeding at baited plots using ultrasonic and water jet devices. *Applied Animal Behaviour Science*, *115*(3–4), 221–232.