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Smart IoT System for Agricultural Pest Control Using Special Frequency Sound Waves

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Abstract

This research develops a prototype of an Internet of Things (IoT)-based cricket pest control system that utilizes ultrasonic waves for rice farming. Addressing global financial losses caused by pests and health risks from chemical pesticides, the main objective is to design an intelligent non-chemical solution. The methodology used is experimental Research and Development (R&D), in which the system is integrated using the ESP32 DO IT Module, a PIR Sensor for cricket detection, and a Passive Buzzer as the ultrasonic emitter (above 20 kHz). The main novelty lies in two aspects: first, the integration of IoT for automatic and targeted repellent activation through PIR Sensor detection; second, the implementation of an adaptive frequency variation mechanism on the ESP32 to periodically change waveform patterns, overcoming the cricket habituation weakness observed in static systems. Testing was conducted with 10 repetitions at 10 different frequency levels (21–30 kHz) in a controlled environment. The results show that the system successfully detects cricket presence and automatically activates the ultrasonic buzzer, achieving the highest success rate of 90% at the optimal frequency range of 25–29 kHz. The conclusion indicates that this prototype offers a smarter, more adaptive, and more efficient solution for cricket pest control in rice farming compared to simple embedded devices.

Keywords: *IoT-based Pest Control, Ultrasonic Repellent, Adaptive Frequency Control, Smart Farming, ESP 32*

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I. INTRODUCTION

A. *Background and Problem Statement*

The agricultural sector holds a highly strategic position and functions as a primary pillar in supporting Indonesia's economy. This role is reflected not only in its contribution to national food security but also in its capacity to provide employment opportunities for the majority of the population, particularly in rural areas. Indonesia is recognized as a country with abundant natural resources that should ideally be utilized optimally to increase agricultural productivity. However, in reality, this potential has not yet been fully maximized. This is evident from the significant gap in agricultural productivity between Indonesia and developed countries such as Japan [1]. This gap indicates that Indonesia continues to face challenges in agricultural technology, land management, production innovation, and the efficiency of modern agricultural systems implemented by developed nations. One of the major obstacles to achieving efficiency and optimal crop yields is the continuous and intensive pressure from pest attacks.

The threat posed by organisms classified as pests or plant diseases is not limited to a single stage. Still, it affects crops throughout the entire agricultural cycle—from the seedling section, vegetative section, and generative section, up to the pre-harvest period and post-harvest storage section [2]. Losses caused by pests are global in nature and threaten the financial stability of the agricultural sector. In Europe and Africa, damage to maize crops has reached a value of US $2.5 billion to US $6.2 billion per year [3]. The persistent impact of pest attacks is highly significant, as demonstrated in rice crops, which can experience yield losses ranging from 24% to 41% due to pest disturbances [2].

Most farmers rely on chemical pesticides to eliminate pests. However, this method has proven to be unsustainable and carries high risks. Globally, there are between 1 and 5 million cases of pesticide poisoning annually, with approximately 220k fatalities. These fatal incidents are caused by continuous use and improper dosage. The primary effect is severe disruption to the nervous system, as pesticides inhibit the function of the *Acetylcholinesterase enzyme*, which is essential for motor system activity [4].

B. *Alternative Solution: Acoustic Technology*

In response to the risks associated with chemical methods, current research is increasingly focused on acoustic-based pest mitigation technologies. Sound waves with specific frequencies, particularly ultrasonic waves (frequencies above 20 kHz), are beyond the range of human hearing [5], yet at the same time have been proven to disrupt the nervous system and auditory organs of pests. These findings indicate that ultrasonic waves provide a highly effective repellent mechanism while remaining safe for both the environment and humans. Other studies also report that behavioral responses in rodent pests are most significant within the frequency range of 30–40 kHz, characterized by physical manifestations such as extreme restlessness, motor disorientation, and loss of body balance. The use of ultrasonic waves is considered a highly strategic approach due to its broad effectiveness, including the potential to damage pest tissues, while simultaneously representing a method that is far more environmentally friendly compared to conventional chemical-based solutions [6]. These empirical findings strongly validate that the use of ultrasonic frequencies, which are undetectable to the human ear, is an effective method for disrupting pest physiological activity [7]. However, the long-term effectiveness of this technology is threatened by the fact that animals possess unique adaptive capabilities to defend themselves against external threats [8]. Therefore, systems must be designed to periodically alter sound patterns to reduce the likelihood of pests adapting to specific sound frequencies.

C. *IoT Integration in Agriculture*

In response to the limitations of traditional pest-control methods that pose high risks and lack efficiency, the Internet of Things (IoT) has emerged as a new paradigm in precision agriculture. Since its inception, IoT has undergone a dramatic evolution in its functional role. Initially, the concept was developed exclusively to optimize complex workflow operations within industrial manufacturing environments and factory floors. However, as the technology matured, its capabilities significantly expanded, transforming IoT into a fundamental driver of digital transformation across various sectors of the global economy. Consequently, IoT integration has become a crucial necessity, even in traditional and essential fields such as agriculture [9].

IoT technology has permeated and enhanced various aspects of the environment in which plants grow. One of its main uses is in water management, where soil moisture sensors are a core component. Thanks to these sensors, IoT systems can monitor soil water levels in real-time and show water pump conditions [10], which aims to make it easier for farmers to check plants and prevent negligence so that plants can grow well with automatically supplied water intake. Furthermore, in the context of handling microclimate factors, the integration of air temperature and humidity (RH) sensors into IoT systems becomes very crucial. Sensors like the DHT11, for example, are widely used in automatic monitoring and control systems to accurately measure and regulate these environmental parameters [11]. Finally, the capability of IoT technology is now enriched with the integration of visual hardware such as the ESP32-CAM camera, which functions as an image capture tool. This camera allows Cam IoT-based smart farming monitoring systems to observe and monitor plant conditions directly (in real-time) and remotely [12]. With this data integration capability, IoT lays the foundation for the creation of smart and adaptive agricultural systems. This allows farmers to make highly precise decisions, effectively reduce the risk of crop failure, and ultimately offer a much more efficient and sustainable solution.

D. Research Gap and Novelty

Although significant efforts have been made in developing non-chemical acoustic pest-repellent devices, a fundamental gap still remains, which this research aims to address. For instance, previous studies on bird deterrence successfully implemented a dual-protection system using pain-threshold frequencies and predator sounds [13]. However, the system operated autonomously as an embedded system utilizing an ATMEGA 328P microcontroller. It did not employ network connectivity, and its sound activation relied solely on pre-scheduled timing mechanisms.

Therefore, this study employs the ESP32 DO-IT Module as the primary control unit and integrates it with a PIR Sensor to directly activate a Passive Buzzer upon pest detection. The main novelty lies in two aspects: first, the integration of IoT to regulate ultrasonic wave emission automatically and with precise targeting; second, the implementation of an adaptive frequency-variation mechanism capable of periodically altering the sound-wave patterns to prevent pests from adapting to a fixed frequency. The ESP32 module enables dynamic and flexible frequency configuration, including fixed-frequency mode, sweep mode (gradual frequency change), and random-frequency mode. This approach provides a significantly smarter, more adaptive, and more efficient solution compared to conventional embedded devices with static frequencies.

II. RESEARCH METHOD

This research employs a quantitative approach, focusing on an experimental method to evaluate the effectiveness of the designed Internet of Things (IoT)–based pest control system. The methodology used is experimental Research and Development (R&D), to design an intelligent, adaptive, and safe pest control system as a sustainable non-chemical solution. Specifically, this study addresses the topic of developing an IoT System for Agricultural Pest Control Using Special-Frequency Sound Waves. The primary objective of this study is to develop an effective, safe, and sustainable pest control system that specifically targets cricket pests, which cause significant agricultural losses. In practical application, this system has the potential to be implemented for controlling cricket infestations in rice crops. The research encompasses prototype development and laboratory calibration sections. The methodology consists of three main stages: (1) Problem Analysis and System Design, (2) Prototype Implementation and Assembly, and (3) System Testing and Effectiveness Analysis. The research workflow is illustrated in the Figure 1.

Figure 1 illustrates the overall research process, starting with problem definition and a literature review to ascertain the capability of sound frequencies in pest control. Once the potential is identified, the next step is Conceptual Design and Proposal Approval. Once the proposal is approved, the implementation section begins with hardware system design, followed by software and algorithm development. Subsequently, the process proceeds to microcontroller programming and program function testing (if unsuccessful, reprogramming is performed). If the program runs well, it moves to prototype assembly and comprehensive testing of both components and the entire system (if there is a failure, it returns to the software or hardware design stage). Ultimately, if all testing is successful, the research concludes with a final trial/test run.

A. Preliminary Study and System Design

This stage holds a crucial role as the theoretical foundation of the research, focusing on the collection and synthesis of quantitative data from previous studies. The data collected covers three main areas: bioacoustics analysis of grasshoppers to identify their hearing frequency range and response, determination of sound wave frequencies proven to affect pest behavior, and identification of suitable and stable Internet of Things (IoT) technology for field application. This data collection was carried out to establish the quantitative independent variable (the frequency range for testing) that would be used in the experimental testing.

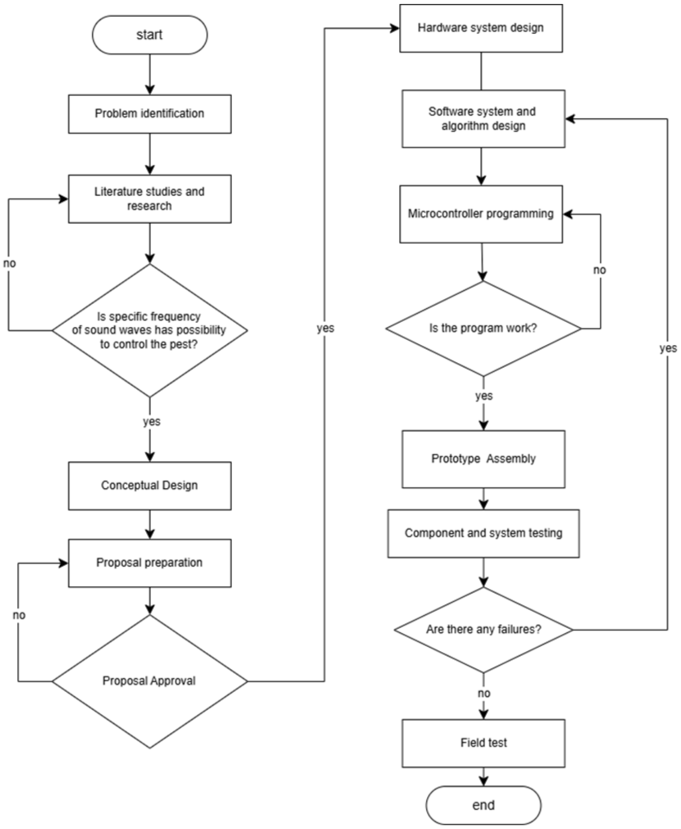

Fig. 1. Research Flowchart

The preclinical study was carried out by conducting a systematic literature review, which analyzed scientific publications from various reputable journals regarding the auditory characteristics and behavioral reactions of grasshoppers to acoustic stimuli. This process included identifying the patterns of grasshoppers' biological responses at specific frequencies, with a particular emphasis on frequencies that cause avoidance or disorientation reactions. The quantitative data successfully collected were then analyzed to identify the best parameters to be implemented in the sound-based pest control system.

In the field of IoT technology, the preliminary research also included a comparative analysis of various microcontroller platforms available on the market. The criteria used for evaluation covered processing capabilities, energy consumption, functional reliability under agricultural environmental conditions, ease of integration with sensor and actuator elements, and economic factors to ensure the solution's capability for large-scale implementation. The findings from this evaluation will serve as a reference in selecting the hardware components to be implemented in the system prototype.

Once the foundational theory was accumulated, the next step was to design the system. Information gathering from previous research was also directed toward determining the most optimal and reliable IoT device for long-term field use, while considering aspects such as cost and energy consumption. This system design was formalized in the form of a Prototype Architecture Block Diagram, which explains the interaction between the sensor unit (PIR), the control unit (ESP32), and the actuator unit (Passive Buzzer). This design serves as a guideline before entering the hardware implementation and integration stage, as well as the firmware development that will be tested.

The architectural block diagram in Figure 2 illustrates the overall operational process of the system, starting with object detection using the PIR (Passive Infrared) sensor, which acts as the system trigger. The signal from the PIR sensor is forwarded to the ESP32, which functions as the main control center that processes the input and executes the program logic. According to the programming integrated into the firmware, the ESP32 activates the Passive Buzzer to generate sound at the frequency determined by the previous analysis.

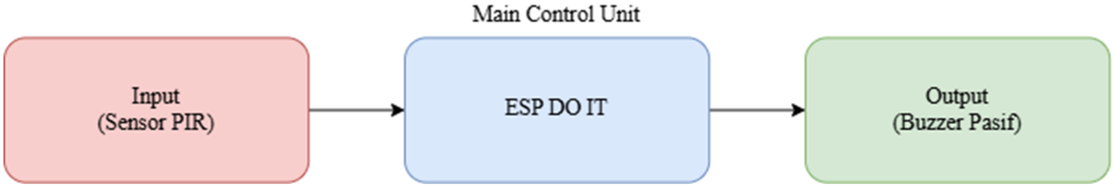

Fig. 2. Prototype System Architecture Block Diagram

B. *Implementation and Prototype Assembly*

The implementation stage is the realization section of the system design that was planned in the previous stage. This process includes the selection of hardware components. The final results prototype can be seen in Figure 3

1) *Hardware Components*

The ESP32 DO IT module serves as the core microcontroller that controls the entire system operation. The ESP32 module is an integrated system series featuring a microcontroller, Wi-Fi (wireless fidelity), and dual-mode Bluetooth on a single board, known for its low cost and low power consumption [14]. To ensure optimal system performance, the ESP32 was chosen because it has a dual-core processor operating up to 240 MHz [15], providing the necessary processing power for high-speed IoT applications.

The Passive Infrared Receiver (PIR) Sensor is implemented as the primary detection unit. It operates passively by monitoring the infrared radiation naturally emitted by pests. This sensor was selected for its ability to identify pest movement and its operational advantages, particularly its high energy efficiency [16], making it ideal for an automatic activation system in an agricultural environment.

A Passive Buzzer was chosen as the acoustic actuator. Unlike an active buzzer, a passive buzzer does not generate sound or tone by itself, thus requiring an input signal. To activate and generate sound from the passive buzzer, an oscillator circuit or a pulse signal from the microcontroller is needed [17]. Because it does not emit a built-in sound, it becomes the ideal choice as it can be programmed to produce high and low tones as required [18]. Therefore, the ESP32 can be used to electronically adjust the frequency of the ultrasonic waves to be tested, providing full flexibility to determine the specific frequency range that is most effective.

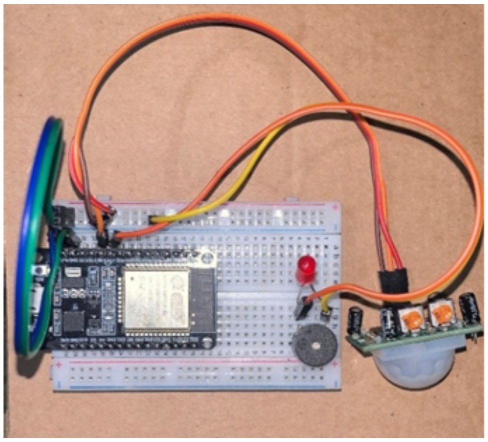

Fig. 3. Prototype Hardware Implementation

2) *Software Development*

This section focuses on the development and implementation of the firmware installed on the ESP32 microcontroller, which also acts as the central control unit of the system. The software coding process is designed based on event-triggered logic to ensure that the system can be activated efficiently and can respond to the presence of pests.

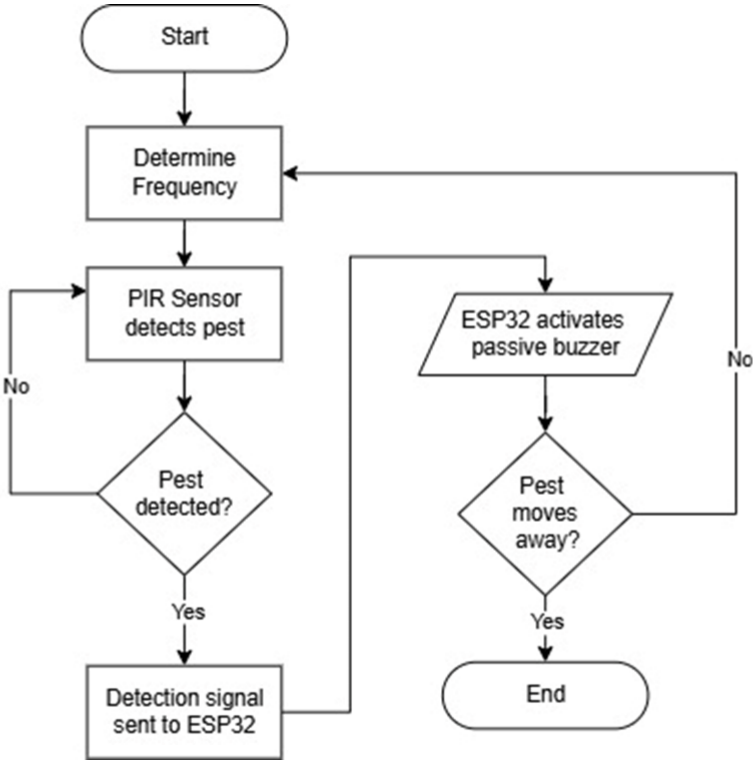

Fig. 4. System Workflow

Figure 4 describes the event-driven system logic implemented within the ESP32 firmware. The process begins with an Initialization step where the system determines the appropriate sound frequency for pest control, based on information derived from previous research. Next, the system enters the Monitoring section, where the PIR sensor begins detecting the presence of pests. This is followed by a condition evaluation to check if a pest is detected. If the answer is 'No,' the system continues the monitoring process using the PIR sensor. If a pest is detected (answer 'Yes'), a detection signal is immediately sent to the ESP32. The main control unit (ESP32) responds to this signal by activating the passive buzzer to generate sound waves intended for deterrent purposes. Once activated, the system performs a simple feedback check: Have the pests moved away? If the pests have not left (answer 'No'), the system returns to the frequency determination stage (repeating the deterrent cycle) until the pests show a response. If the pests are detected moving away (answer 'Yes'), this indicates that the deterrent effort has been successful, and the system program terminates (End), allowing the system to return to a standby mode for energy efficiency.

C. System Testing and Effectiveness Analysis

This section serves as the critical validation stage of the entire research, aiming to quantitatively measure the effectiveness of the system prototype under controlled conditions in a laboratory or designated testing facility. The primary objective is not merely to observe system function but to gather robust, empirical data that verifies the system's core capability: the ability to deter pests acoustically.

Specifically, the ultimate goal is to pinpoint the most effective sound wave frequency, termed the optimal frequency, for either actively repelling pests or inducing a measurable negative physiological or behavioral effect on them. By conducting these trials in a highly controlled setting, we minimize external variables, ensuring that any observed changes in pest behavior are directly attributable to the ultrasonic stimuli emitted by the prototype. This rigorous approach is essential for providing scientific validity to the claim that the event-triggered acoustic intervention offers a viable, non-chemical pest control solution. The success of this section directly determines the practical utility of the entire IoT prototype before any potential field deployment.

1) Experimental Testing Procedure

The system trial was conducted using a Post-test Only Control Group Design experimental design in a controlled environment (a closed box) using pest samples relevant to the rice farming environment.

1. Trial Environment The trial was conducted inside a 50x30 cm container at room temperature and placed in a silent location. Ten pests were prepared in the container, and the trial will be repeated 10 times using different ultrasonic sound frequencies.
2. Treatment This procedure as seen in Table I applies a pure experimental approach by varying the frequency as a quantitative independent variable. The dependent variable is the pest avoidance behavior, which is measured by the number of individual pests moving away from the Buzzer sound source within a specific duration. We use ten frequency points within the ultrasonic range of 20k Hz to 30k Hz as the treatments.

TABLE I. FREQUENCY RANGE

Variable	**Frequency**
f1	21k Hz
f2	22k Hz
f3	23k Hz
f4	24k Hz
f5	25k Hz
f6	26k Hz
f7	27k Hz
f8	28k Hz
f9	29k Hz
f10	30k Hz

During the trial, the system was activated by the PIR Sensor when the pest entered the detection zone, triggering the Passive Buzzer. The testing was conducted with ten replications ($n = 10$) for each frequency level emitted to ensure internal validity and minimize bias.

2) Data Collection

The observation results were recorded to validate the claim that targeted (event-triggered) activation is effective in intervening in pest attacks. The observation results were recorded to validate the claim that targeted (event-triggered) activation is effective in intervening in pest attacks.

D. Data Analysis Method

The data collected from the effectiveness tests were analyzed quantitatively using descriptive statistical methods to identify response patterns of the pests to the variations in ultrasonic frequency. This analysis focused on calculating the Success Rate E at each tested frequency, which represents the system's effectiveness in repelling the cricket pests from the protected area. The Success Rate was calculated from the percentage of pest individuals that showed avoidance behavior compared to the total pest samples tested. Avoidance behavior was strictly defined as movement away from the Buzzer sound source by a minimum distance of 8 cm from the initial position within a duration of 60 seconds after system activation. This metric was chosen because it reflects the pests' natural defensive response to a threatening stimulus, which is the primary indicator of the ultrasonic wave's effectiveness as a non-lethal repellent method. The calculation of the success rate was determined using Equation 1:

$$E = (\frac{I_A}{I_T}) \times 100\% \tag{1}$$

In Equation 1, E represents the Success Rate (Effectiveness) of the system, expressed as a percentage (%). I_A is the Number of Avoiding Pest Individuals (i.e., pests that moved away from the Buzzer sound source according to the established criteria), and I_T is the Total Number of Pest Individuals in the Trial (referring to the total of 10 pest samples tested at each frequency). To ensure the reliability of the results, each frequency was tested with ten repetitions (n=10), resulting in a total of 100 test observations (10 frequencies × 10 repetitions). Data from each repetition were systematically recorded in an observation sheet that included: the frequency emitted, the number of avoiding individuals, the success rate, and notes on specific observed behaviors.

TABLE II. ULTRASONIC FREQUENCY EFFECTIVENESS TEST RESULTS ON PESTS

Number	**Test Frequency (kHz)**	**Number of Pests Repelled/Avoided**	**Success Rate (%)**	**Remarks / Notes**
1	21	6	60%	The lower limit of the effective ultrasonic range tested
2	22	6	60%	
3	23	7	70%	Begins to show an increased response
4	24	8	80%	Strong response: restlessness and discoordination
5	25	9	90%	
6	26	9	90%	Optimal frequency range
7	27	8	80%	
8	28	9	90%	
9	29	9	90%	
10	30	7	70%	Gradual decrease in effectiveness

III. RESULTS AND DISCUSSION

A. *Prototype and System Functionality Test Results*

The initial phase of this research was a crucial step that verified the functionality of every main component and the system as an integrated whole. The functionality testing confirmed that the ESP32 DO IT Module, which serves as the core IoT microcontroller, successfully connected to the IoT network and executed the designed control firmware. This successful wireless connectivity is essential for supporting the remote monitoring and control capabilities that are the main characteristics of this IoT system. Furthermore, the ESP32 module was proven capable of electronically regulating frequency variation. This adaptive frequency regulation functionality is the main novelty of this research, specifically designed to prevent the occurrence of adaptation or habituation of pests to static ultrasonic wave patterns, thereby increasing long-term effectiveness.

Meanwhile, input verification showed that the PIR Sensor (Passive Infrared), which is responsible for automatically detecting the movement of pest objects, was able to operate accurately within the determined radius. The accuracy of this detection validates the event-triggered activation mechanism, which is key to the system's power efficiency, as the system is only activated when pest movement is detected.Finally, testing on the system's actuator proved that the Passive Buzzer was successfully controlled electronically by the ESP32 to generate ultrasonic waves in the specific frequency range, namely above 20 kHz. This frequency range is scientifically targeted to disrupt the nervous systems of pests, such as mice and insects, without harming humans. This functionality confirms that the prototype has met all architectural design requirements and is ready for effectiveness testing in a field environment.

B. *Analysis of Ultrasonic Frequency Effectiveness on Pests*

The testing of this system's effectiveness was conducted in a controlled environment using a strict experimental protocol. This involved 10 replications at 10 different frequency levels within the ultrasonic range of 21 kHz to 30 kHz. The selection of this frequency range was based on a literature review indicating that ultrasonic waves above 20kHz are beyond the human hearing threshold but are still detectable by the auditory systems of insects, particularly crickets, which possess tympanal organs sensitive to acoustic vibrations. Ten frequency points were chosen with a 1 kHz interval to provide sufficient resolution in identifying the optimal frequency range.

Based on the observations presented in Table II, it is evident that the system's effectiveness has a close and direct correlation with the ultrasonic frequency used in signal transmission. Specifically, the highest success rate in repelling pests—achieving an effectiveness percentage of 90%—was identified across several ultrasonic frequency ranges deemed optimal: 25kHz, 26kHz, 28kHz, and 29kHz. This finding provides strong, empirical evidence that the developed IoT-based pest control system is capable of functioning effectively within specific frequency ranges of the ultrasonic spectrum. This result also aligns with previous scientific studies which affirm that sound waves with frequencies above 20 kHz have significant potential to disrupt insect activity and repel pests from agricultural areas [5].

Additionally, the experimental data show that the effectiveness level remains in the high category 90% within that frequency range. However, when the frequency increases to 30 kHz, there is a rather noticeable drop in effectiveness to approximately 70%. This decrease can be interpreted as a biological phenomenon related to the limits of the pest species' auditory sensitivity or their optimal resonance point used as the test subject. In other words, the pests exhibit the most sensitive response in the frequency range around 25 kHz, and effectiveness declines when the frequency moves higher than that range.

Furthermore, this experiment confirms the novelty contribution of the conducted research. The developed system doesn't just emit ultrasonic waves statically; it is also capable of performing adaptive frequency variation. This capability successfully overcomes the possibility of habituation of pests to a single frequency. Thus, it's proven that the frequency range between 25 kHz and 29 kHz is the most optimal working range for both preventing habituation and achieving high repellent effectiveness. This confirms the superiority of the variable frequency approach in the proposed ultrasonic-based IoT pest control system.

C. IoT Integration Benefits and System Performance

The significant contribution of this research lies in the full integration of IoT and event-triggered activation. Unlike pest control systems based on timers or fixed schedules, this prototype only activates the Passive Buzzer when the PIR Sensor detects a threat, supported by the firmware logic that manages frequency variation. This smart control not only enhances the effectiveness of pest repulsion with precise targeting but also ensures significant power efficiency because the Buzzer component is only turned on when necessary. Overall, these findings position the proposed system as an advanced solution in precision agriculture technology (smart farming) in Indonesia.

What distinguishes this system from a simple embedded device is the integrated IoT capability on the ESP32. The ESP32 module is equipped with a built-in WiFi chip that allows for wireless network connectivity, opening up possibilities for monitoring, remote control, and data analysis that are unavailable on conventional microcontrollers like the Arduino UNO. The prototype developed in this research implements a responsive activation logic that only engages the Passive Buzzer when the PIR Sensor detects a genuine threat in the form of pest movement within the protected area.

IV. CONCLUSIONS AND FUTURE WORKS

This research successfully designed and implemented an efficient, event-triggered IoT-based pest control system prototype, addressing the limitations of static acoustic systems and conventional chemical methods. The system, which utilizes the ESP32 DOIT module and a PIR Sensor, demonstrated reliable, event-triggered activation, ensuring the Passive Buzzer is only active upon movement detection. This approach maximizes energy efficiency and operational precision. Experimental findings validate the efficacy of the acoustic mechanism, confirming that ultrasonic waves in the optimal frequency range of 25 kHz to 29 kHz significantly disrupt pest activity and trigger avoidance behavior, achieving a peak success rate of 90%. The primary scientific contribution (novelty) lies in the system's capacity for dynamic frequency variation, which is integrated directly through the ESP32. This capability fundamentally eliminates the risk of pest habituation over time, providing a viable, intelligent, and sustainable model for green and digital farming in the critical agricultural sector.

To maximize the impact and performance of this system in the future, it is recommended that the focus of subsequent research be significantly expanded into the biological and agronomic scopes. This includes broadening the trials to different pest species (such as mice or other insect groups) to validate the effectiveness of the optimal frequency range beyond locusts. Furthermore, the integration of the system into various types of crop commodities (not just rice) is highly recommended to test the system's scalability and adaptability. The intelligence aspect of the system also needs enhancement by implementing Machine Learning (ML) algorithms on the ESP32 to automate the adaptive identification and optimization of the repulsive frequency based on collected log data. Lastly, to ensure continuous operation in fields without electricity access, it is necessary to develop a stable and autonomous power system, such as battery integration with a solar-cell system.

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