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Design And Implementation Of A Solar-Powered Intelligent Mcu-Based Bird Deterence System For Rice Farmers

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ABSTRACT: Bird infestations pose a significant challenge in rice farming, leading to considerable crop damage and reduced yields for farmers. Conventional techniques for frightening birds, such as hand clapping, using scarecrows, and producing noise, require a great deal of effort and are often ineffective. This research presents the design and implementation of a microcontroller-driven Bird Control System that autonomously detects bird activity and deters them using distress sounds. The setup incorporates an ESP32 microcontroller with the RCWL-0516 microwave radar sensor to identify bird activity within 9 meters of distance. Once motion is detected, the controller activates an audio amplifier that plays pre-recorded bird distress calls through a speaker, successfully driving away the birds. The system was implemented on hardware for practical testing. Results indicated a fast response time of less than one second, consistent detection performance, and an average bird deterrence success rate of 85 percent. The system operates on a solar-charged 3S Li-ion battery pack, ensuring continuous operation in isolated farming environments. With low power consumption, autonomous operation, and environmentally friendly design, this bird deterrent system provides a cost-effective and sustainable solution for agricultural producers. This research demonstrates the application of modern embedded systems and sensors in addressing agricultural challenges, improving productivity, and reducing post-harvest losses.
KEYWORDS: Pest Bird Management, Rice Cultivation, Avian Crop Depredation, Integrated Pest Management (IPM), Red-billed Quelea, Synchronized Planting, Smart Scaring Technology, Bird-Resistant Rice Varieties

INTRODUCTION: Agricultural productivity, particularly in cereal crops like rice stands as a cornerstone of food security and economic stability across Nigeria and the broader West African sub-region, serving as a primary staple for millions. Its cultivation, however, is challenged by a myriad of biotic and abiotic factors, with avian pests emerging as one of the most devastating threats. Birds, particularly granivorous species such as the Village Weaver, various sparrow species, and the highly destructive Red-billed Quelea, inflict significant damage on rice crops, especially during the critical maturing and pre-harvest stages. These birds feed voraciously on ripening grains, leading to substantial quantitative and qualitative losses for farmers (FAO, 2021; Adekola et al., 2020).

The economic repercussions of bird damage are profound. Historically, farmers have reported perceived losses of up to 75% of total output in some regions, with up to 50% of production costs allocated to bird scaring (Ojo, 2007). While empirical studies often show slightly lower, yet still considerable, damage levels, the impact remains severe. For instance, in Ogun State, Nigeria, estimated losses due to birds ranged from 7% to 26%, with the Village Weaver identified as a principal pest (Ojo, 2007). Across Africa, the Red-billed Quelea alone is estimated to cause annual crop damage in the tens of millions of US dollars (Oduntan et al., 2015), with specific reports indicating an average annual economic loss of €7.1 million, translating to around 13.2% of potential rice production in the Senegal River Valley (De Mey et al., 2012). In Nigeria, bird-related crop losses have been reported to range between 26% to 50% depending on region and crop type (Odewumi & Audu, 2024; Mathew et al., 2025). More alarmingly, in 2023, reports indicated that Kebbi State alone lost an estimated 75,000 to 86,000 hectares of rice farms to Quelea birds, translating to substantial financial losses for farmers (Daily Trust, 2023). Similarly, in the Zabarmari rice fields of Borno State, farmers reported seasonal yield losses of up to 2.4 tons per hectare, valued at approximately ₦2.4–2.88 million (Mathew et al., 2025). National surveys have corroborated these findings, showing average losses of about 30% in affected regions (NAERLS, 2022). These staggering figures underscore the urgent and persistent need for effective and economically viable bird deterrent systems specifically tailored to the diverse agricultural landscapes of Nigeria.

Traditional bird-scaring methods, such as the deployment of scarecrows, manual shouting, and the use of metal clanging, are deeply rooted in local farming practices. However, these methods are inherently labor-intensive, demand constant human presence, and exhibit limited effectiveness, as birds often habituate to static or repetitive stimuli over time (Osinubi & Nwankwo, 2017; Ahmad et al., 2018). While physical barriers like bird netting offer high effectiveness, their high cost and impracticality for large-scale cultivation or smallholder farms often render them unfeasible (Osinubi & Nwankwo, 2017). The limitations of these conventional approaches highlight a critical gap in current crop protection strategies, necessitating innovative and sustainable alternatives.

In recent years, significant advancements in embedded systems and sensor technology have opened new avenues for automated agricultural protection. The integration of microcontrollers, such as the ESP32, with sensory devices like Passive Infrared (PIR) and microwave radar (e.g., RCWL-0516) sensors, enables precise detection of bird presence. This detection can then trigger automated deterrents, offering a more efficient and less labor-intensive solution. Acoustic deterrents, particularly the broadcast of bird distress and predator calls, have demonstrated considerable efficacy in reducing bird presence in vulnerable areas (Bomford & O'Brien, 1990; Jackson & Foster, 2020). These bioacoustics systems leverage birds' natural instincts, creating an environment they instinctively avoid, and can be designed with randomized playback patterns and varying frequencies to prevent habituation, ensuring long-term effectiveness (Baral et al., 2023; Jackson & Foster, 2020). The potential for solar energy integration further enhances the sustainability and autonomy of such systems, making them particularly suitable for remote agricultural settings without reliable grid access (Makinde et al., 2024; IRJMETS, 2025). This study 'the design and implementation of an automated system' therefore leverages motion detection and bioacoustics principles to detect and repel avian pests from rice fields. By providing a cost-effective, environmentally friendly, and efficient solution, this research aims to mitigate crop loss, improve agricultural productivity, and contribute to enhanced food security in Nigeria.

UNDERSTANING THE PROBLEM: Despite the critical importance of rice production to Nigeria's food security and economy, bird damage remains a pervasive and escalating challenge. The existing strategies and limitations give rise to several key problems. These include: substantial economic loss and reduced food security, as the significant and often underreported economic losses due to bird infestation directly impact farmers' livelihoods, reduce national food output, and exacerbate food insecurity, particularly for a rapidly growing population, rendering rice farming less profitable and sustainable for many smallholder farmers. Another problem is the reliance on ineffective and labor-intensive traditional methods, such as human guarding, scarecrows, and noise-making, which are unsustainable, highly labor-intensive, require constant monitoring, and are prone to bird habituation, leading to diminishing returns over time and increasing operational costs for farmers. Furthermore, there is a lack of affordable and accessible automated deterrent systems; while advanced automated bird deterrents (e.g., laser systems, drones, complex AI-driven solutions) exist, they are often prohibitively expensive and technologically complex for the average small-scale Nigerian farmer, highlighting a critical need for an automated, robust, and cost-effective solution that is easy to deploy and maintain in rural agricultural settings.
Environmental concerns with current practices also pose a problem, as some conventional or desperate measures, such as the indiscriminate use of chemicals or harmful physical traps, pose environmental risks and can negatively impact non-target species, raising ecological and ethical concerns, thus necessitating a humane and environmentally benign solution for sustainable agriculture. Finally, there is limited integration of modern technology in small-scale agriculture, where the slow adoption of modern, smart farming technologies in developing regions contributes to persistent agricultural inefficiencies, making bridging this technological gap with practical, accessible solutions crucial for modernizing the agricultural sector. The primary aim of this research is to design and implement a cost effective, solar powered microcontroller-based bird control system using bird distress sounds triggered by motion detection, thereby reducing crop loss and improving agricultural productivity in rice farms. The objectives were thus defined as follows:

1. To develop a system that accurately detects bird movement within a defined area using an RCWL-0516 microwave radar.
2. To integrate a DF Mini MP3 player module to effectively play preloaded species-specific distress and predator sounds via an external speaker upon bird detection.
3. To design and implement a sustainable power solution for the system, utilizing a rechargeable battery supported by solar energy harvesting.
4. To conduct experimental testing of the developed system in a simulated farm environment to evaluate its effectiveness in reducing bird activity and deterring avian pests.

SIGNIFICANCE OF THE STUDY: This research holds significant implications for advancing agricultural practices and addressing food security challenges in Nigeria and similar developing regions. By demonstrating the practical application of embedded technology in agricultural protection, it offers a viable solution to a long-standing problem.
Firstly, the proposed system provides a cost-effective and labor-saving alternative to traditional bird-scaring methods. Automating the deterrence process significantly reduces the need for constant human presence, allowing farmers to reallocate labor to other critical farming activities and ultimately lowering operational costs.
Secondly, it contributes directly to increased crop protection and enhanced yields. By effectively repelling birds, the system minimizes pre-harvest losses, leading to higher productivity and improved profitability for farmers. This directly translates to greater food availability and economic stability for farming communities.
Thirdly, the system is designed to be environmentally friendly and humane. Unlike methods involving harmful chemicals or physical traps, this acoustic deterrent system does not injure or kill birds, aligning with principles of sustainable agriculture and biodiversity conservation. The use of solar energy further reduces its environmental footprint.
Furthermore, by utilizing readily available and relatively inexpensive components, the system is designed for replicability and scalability, making it accessible even to smallholder farmers who often lack access to advanced agricultural technologies. This fosters the adoption of modern farming practices at the grassroots level.
Finally, this study contributes to the burgeoning field of precision agriculture and smart farming in developing contexts. It serves as a proof-of-concept for how localized, automated solutions can be developed to address specific agricultural challenges, promoting technological innovation and resilience within the sector. It also lays the groundwork for future research into more sophisticated, AI-driven bird detection and deterrence systems.

MATERIALS AND RESOURCES: The research design and implementation was guided by the principle of utilizing budget-friendly and readily available electronic components. This constraint influenced the selection of sensors and modules, prioritizing a balance between performance and affordability. Due to these cost and availability limitations, the system does not incorporate high-end features such as advanced real-time image processing for bird identification, complex AI-based classification of bird species, or sophisticated directional sound broadcasting. The focus remained on robust, basic motion detection and effective, broad-spectrum acoustic deterrence.

FINANCING: The research operated under a modest budget, which played a significant role in determining the choice of hardware components and the overall complexity of the system. The selected components (ESP32, RCWL-0516, DF Mini MP3 player, basic speaker, solar panel, and battery) represent a cost-effective solution suitable for small-scale deployment and potential adoption by individual farmers or small cooperatives. This financial constraint necessitated a pragmatic approach, focusing on core functionality and reliability rather than incorporating expensive, cutting-edge technologies. The aim was to develop a practical prototype that could demonstrate effectiveness within a realistic budget for its target users.

LITERATURE REVIEW

BIRD PESTS AND AGRICULTURAL DAMAGE IN NIGERIA: In Nigerian cereal production methods, birds continue to be a significant hindrance. Because of their migratory habits, feeding habits, and adaptive intelligence, they pose a serious threat to food security, especially in economies that rely heavily on grain. Bird infestations frequently pose a threat to smallholder and commercial farmers in areas where rice, millet, and sorghum are the predominant crops, such as the Guinea-Savanna (Kwara, Niger) and the Sudan-Savanna belt (Borno, Kebbi) (FAO, 2019; Salami & Adebisi, 2023). The bird's developed efficiency in utilizing concentrated, high-energy food sources a characteristic that farmed monoculture fields exemplify exacerbates this issue (Adekola et al., 2020). While increasing output, the switch to irrigated rice farming has inadvertently produced consistent, year-round feeding grounds, which has increased local density and decoupled bird populations from seasonal food constraint. The Red-billed Quelea is one of the most destructive species; its numbers are thought to number in the hundreds of millions throughout sub-Saharan Africa. Often referred to as a "living cloud," its swarming movement and coordinated feeding habits can cause total field destruction in a matter of hours (21st Century Chronicle, 2022). According to CABI (n.d.), a flock of two million Quelea birds may consume almost 20 tons of grain in a single day, and a single bird can ingest 10 grams of grain each day. Other species aggravate the injury. Ripening grains are also severely damaged by the extremely adaptive House Sparrow, the Bronze Mannikin, and the Village Weaver, which is renowned for its careful nest-building and flock-based feeding (Oluwatayo & Ojo, 2021). Specifically, the Village Weaver not only consumes grain but also damages stalks by tearing strips of plant material for nest construction, causing a form of indirect yield loss that is often overlooked in damage assessments (Adekola et al., 2020).

The size of these losses is demonstrated by empirical evidence. According to Mathew et al. (2025), farmers in Borno State may lose up to ₦2.88 million every season due to average rice losses of 2.4 tons per hectare. Similarly, Odewumi & Audu (2024) reported 26–50% crop losses in Kwara State, confirming that one of the main reasons for yield decline is still avian depredation. National grain losses from bird pests ranged from 25 to 35%, depending on the agro-ecological zone, according to the NAERLS (2022) agricultural performance report. These losses are especially important during the grain-filling and milk-ripening phases. The developing kernels are soft, very tasty, and easily digested at this phenological stage because they contain a lot of moisture and simple carbohydrates. For birds, particularly those feeding their young, this offers an ideal, high-energy food source (Salami & Adebisi, 2023). By deftly squeezing the liquid endosperm from the husk while perched on the stalk, the birds attack by "milking" the kernel, leaving behind an empty, seemingly unharmed husk. The actual damage is frequently grossly underestimated as a result of this deliberate "milking" (Ojo, 2007).

Quelea flocks' seasonal migration, which coincides with crop maturation phases, exacerbates the issue. This synchronization is a developed tactic rather than a coincidence, and it is currently being exacerbated by the Sahel's desertification due to climate change, which drives flocks farther south into agricultural areas (Salami & Adebisi, 2023). Farmers are deterred from growing rice and millet commercially by the ensuing food shortages and financial losses. This leads to a vicious cycle of food insecurity and poverty. When farmers borrow money for fertilizer and seed, they risk aversion, and a reluctance to invest in subsequent planting seasons or switch to new, high-yield cultivars (Adewale & Okoro, 2023). The urgent need for efficient, automated deterrent systems that are affordable and sustainable for local conditions is highlighted by Adewale & Okoro's (2023) observation that many farmers in North Central Nigeria have switched to less vulnerable and frequently less profitable tuber crops like cassava.

CLASSICAL METHODS FOR BIRD CONTROL: For bird control, Nigerian farmers have historically used physical labor and inexpensive methods. These techniques, which have been used for many generations, are based on firsthand observation and the availability of resources right away. These consist of netting, nest destruction, physical barriers like flagging and "bird lines", human scaring, static visual deterrents like scarecrows, and dynamic visual deterrents like reflective tape (Osinubi & Nwankwo, 2017). Despite their inventiveness, these techniques are nearly always accompanied by high labor costs and a gradual decline in efficacy.

Scaring by hand is the most traditional and popular technique. From sunrise until sunset, farmers or, more frequently, hired laborers and children patrol the fields. To produce a continuous cacophony, they employ rattles, whistles, sticks pounded against tins or metal gongs, and drums (Umar & Bello, 2020). Despite being successful at first, it requires ongoing, careful attention and has little lasting effect. Bird habituation, a type of learnt behavior in which the animals stop reacting to a repeated stimulus, is the main disadvantage.

The primary drawback is bird habituation, a form of learned behavior where the animals cease to respond to a repeated stimulus that they discover is not associated with any real danger (Ahmad et al., 2018). Birds, especially intelligent species like weavers, quickly learn the "schedule" of the patrols and simply wait in nearby trees, returning the moment the scarers are absent. The physical toll on farmers and the opportunity cost of lost labor make it unsustainable for large fields. This method also has a significant, often overlooked social cost: the use of child labor for bird scaring is common, which directly interferes with school attendance during peak harvest seasons.

Scarecrows, constructed from straw and old clothing, attempt to mimic human presence. However, avian intelligence is frequently underestimated. Akinwumi & Davies (2019) found that birds, particularly corvids and weavers, often adapt within days, recognizing the static, non-threatening nature of the object. Effectiveness plummets to below 20% after the first week. Similarly, reflective objects like CDs, foil strips, and "bird lines" (long strands of reflective tape stretched across a field) create temporary flashes but are entirely dependent on wind and bright sunlight. They fail in low-light, overcast, or still-air conditions, which are precisely the conditions common during early morning and late evening, the peak feeding times for most pest species (Adekunle & Lawal, 2018).

Nest destruction, which targets breeding colonies of weavers and Quelea, is labor-intensive and ecologically problematic. While effective in isolated, localized communities, it requires significant manpower to locate and destroy thousands of nests (Ibrahim & Musa, 2021). Furthermore, it is often a non-selective, destructive process that can involve cutting down valuable shade or fruit trees that host the colony, or using fire, which damages the local ecosystem. Crucially, this method is completely ineffective against the primary threat: migratory populations of Quelea that breed hundreds or thousands of kilometers away and arrive as a non-breeding, nomadic feeding swarm (Umar & Bello, 2020).

Bird netting provides near-complete exclusion and is highly effective in high-value horticulture. However, its application for large, open-field rice paddies is economically unfeasible. The capital cost for durable, UV-stabilized netting is prohibitive for smallholder farmers. Moreover, the nets are prone to damage by wind, large animals, or theft, and their installation and removal require significant, careful labor (Nwosu & Okorocha, 2022). Most importantly, all these traditional methods lack automation and adaptability, leading to short-lived success, high labor demands, and recurring, demoralizing yield losses (Adekunle & Lawal, 2018).

TECHNOLOGICAL APPROACHES TO BIRD CONTROL: In response to the limitations of traditional methods, various technological solutions have emerged for agricultural pest control, aiming to provide more efficient and less labor-intensive alternatives. These technologies often leverage sound, light, or physical mechanisms to deter birds:

Propane Bird Cannons: These devices produce loud, sudden explosions at timed intervals, mimicking gunshots or other startling noises. They are effective in scaring birds over large areas due to their high sound intensity. However, their effectiveness can diminish over time as birds habituate to the noise if the timing and location of blasts are not varied (Bomford & O'Brien, 1990). Moreover, their loud nature can cause noise pollution, leading to complaints from nearby communities or livestock, and they require regular refilling of propane tanks (Smith & Jones, 2017).

Ultrasonic Bird Repellents: These devices emit high-frequency sound waves (above the human hearing range) that are supposed to be irritating or disorienting to birds. The premise is that birds will avoid areas where these sounds are present. However, the efficacy of ultrasonic repellents is highly debated in scientific literature. Most birds are sensitive to sounds from about 1 to 4 kHz, with an upper threshold generally around 10-15 kHz (Curtis, 1996; Avery et al., 1992). Ultrasonic frequencies (above 20 kHz) are largely considered ineffective for bird deterrence by the broader scientific consensus, as most birds do not hear in this range (Avery et al., 1992).

Automated Sound Systems (Bioacoustics): These systems play recorded sounds, typically predator calls (e.g., hawk screeches), distress calls (sounds made by birds in danger), or alarm calls (sounds warning of danger). The idea is to exploit birds' natural fear responses. (Bomford & O'Brien, 1990) extensively reviewed the use of sonic deterrents, concluding that while they can be effective, their success is highly dependent on several factors: precise timing of deployment, appropriate volume levels, and the specific type of sound used, as birds can habituate to repetitive, non-threatening sounds. More advanced systems incorporate random playback patterns and a variety of sounds to prevent habituation, which is crucial for long-term effectiveness as birds quickly adapt to repetitive, non-threatening stimuli (Jackson & Foster, 2020; Baral et al., 2023).

Laser Deterrent Systems: These systems use automated green lasers to project beams of light across fields. The moving laser beam is perceived by birds as a physical threat or an approaching predator, causing them to flee. Laser deterrents have shown promising results, particularly in low-light conditions or at dawn/dusk, and can cover large areas with minimal disturbance to non-target species (Bishop et al., 2019). However, they are generally high-cost solutions, require careful aiming to avoid human or animal eye exposure, and their effectiveness can be reduced in bright daylight (Chen & Li, 2021).

Despite the advancements in these technological solutions, a significant barrier to their widespread adoption in developing countries like Nigeria remains their prohibitive cost. High-tech systems, often imported, are frequently beyond the financial reach of small-scale farmers who constitute the majority of agricultural producers in the region (Okafor & Eze, 2022). Furthermore, many of these systems require consistent power supply, which can be unreliable in rural areas, and may demand specialized maintenance, posing additional challenges.

BIOACOUSTICS DETERRENT FREQUENCIES: Effective bioacoustics deterrents rely on sounds that are within the audible range of the target bird species and are perceived as a threat or discomfort. Research indicates that most bird species are most sensitive to sounds within the frequency range of approximately 1 to 4 kHz, though their hearing can extend up to 8-15 kHz depending on the species (PeerJ., 2022; Curtis, 1996). For example, pigeons exhibit peak sensitivity between 1-2 kHz, with an upper limit around 10 kHz (Curtis, 1996).Sounds in the 4-6 kHz range, particularly if frequency-modulated, have also shown effectiveness in eliciting avoidance behaviors, as these frequencies may be more easily detected above lower frequency background noise experienced by flying birds (PeerJ., 2022).

Crucially, ultrasonic frequencies (above 20 kHz) are generally ineffective for bird deterrence, as most avian species do not perceive sounds in this range (Avery et al., 1992; Woronecki, 1988). While some recent studies have explored the use of frequencies up to 35 kHz for bird repellents in specific contexts (Li et al., 2024), the broader scientific consensus and practical application for general bird deterrence focus on the audible spectrum. The design of effective bioacoustics systems, therefore, prioritizes frequencies within the typical bird hearing range to ensure maximum impact and a balance between efficacy and human tolerance, avoiding the use of sounds that are inaudible to humans but also largely ineffective for birds. Furthermore, to prevent habituation, these systems often incorporate randomized playback patterns and variations in pitch and sequence, rather than continuous or repetitive tones (Jackson & Foster, 2020; Baral et al., 2023).

EMBEDDED SYSTEMS AND MICROCONTROLLER-BASED SOLUTIONS: The rapid evolution and decreasing cost of microcontrollers and embedded systems have opened new avenues for developing practical, low-cost, and efficient automated solutions for various agricultural challenges, including pest control. The integration of sensors with programmable microcontrollers offers a paradigm shift from reactive, labor-intensive methods to proactive, intelligent systems.

Devices such as the ESP32, a powerful, low-cost Wi-Fi and Bluetooth-enabled microcontroller, are particularly well-suited for agricultural applications due to their versatility, low power consumption, and robust processing capabilities (Rose et al., 2020). These microcontrollers serve as the "brain" of automated systems, allowing for the processing of sensor data and the triggering of appropriate deterrent actions.

When combined with various motion sensors, these systems can accurately detect the presence of approaching birds. Common sensor types include:

Passive Infrared (PIR) Sensors: These sensors detect changes in infrared radiation caused by the movement of warm bodies, such as birds. They are simple, low-cost, and effective for detecting movement within a certain range (Kumar et al., 2021).

RCWL-0516 Microwave Radar Sensors: These sensors emit microwave signals and detect changes in the reflected signal caused by movement. They offer advantages over PIR sensors, such as better penetration through non-metallic objects (e.g., light foliage) and less susceptibility to temperature changes (Wang & Li, 2022).

Ultrasonic Sensors (e.g., HC-SR04): While less common for bird detection due to their narrow beam and susceptibility to environmental factors, they can be used for proximity sensing in certain contexts (Ahmad et al., 2018).

Upon detection of a bird, the microcontroller can trigger a range of auditory deterrents. Sound modules like the DF Mini MP3 player are inexpensive and easily integrated, allowing for the storage and playback of various pre-recorded sounds. These sounds can include:

Distress Calls: Recordings of birds in distress, which naturally trigger alarm and avoidance behavior in other birds of the same or similar species (Stiles & Johnson, 2018).

Predator Calls: Sounds of natural avian predators (e.g., eagles, hawks) that evoke a fear response.

Loud, Sudden Noises: Irregular, non-repetitive bursts of sound that startle birds without allowing them to habituate.

Recent studies have increasingly demonstrated the effectiveness of these automated, sensor-based deterrents in reducing crop damage. For instance, (Kumar et al., 2021) showcased a prototype system using PIR sensors and an Arduino microcontroller to activate sound deterrents, reporting a significant reduction in bird visits and subsequent crop damage in experimental plots. Similarly, (Adedayo & Olaniyi, 2023) developed a solar-powered, microcontroller-based system for maize farms in Oyo State, Nigeria, which minimized the need for human intervention and maintained constant field surveillance, leading to improved yields. The integration of solar power further enhances the sustainability and independence of these systems from unreliable grid electricity, making them particularly suitable for remote rural farming communities (Nwankwo & Osinubi, 2021). This approach not only reduces labor costs but also ensures consistent deterrence, overcoming the limitations of manual and static methods.

SYSTEM ARCHITECTURE AND OVERVIEW

The bird control system was designed on a modular basis, a foundational engineering principle where distinct functional units are developed and tested independently before being integrated. This approach significantly simplifies troubleshooting, maintenance, and future scalability. A fault in the power system, for example, can be diagnosed and repaired without affecting the control or sensing units. At the core of this architecture is the ESP32 microcontroller, which functions as the central processing unit, or "brain," of the system. It is responsible for coordinating all sensing, data processing, and actuation tasks.

The system's operation is defined by a straightforward, continuous "sleep-wake-act" loop, which is critical for power conservation. The sensing unit, a microwave radar module, constantly monitors the environment for motion. The vast majority of the time, the microcontroller is in a deep-sleep mode, consuming minimal power. When the sensor detects motion, it sends an interrupt signal that wakes the microcontroller. The control unit then processes this signal, executes its logic, and activates the sound playback module. The sound emitted through the loudspeaker consists of randomized bird distress calls and predator sounds. This randomization is a key design feature to prevent bird habituation, a common failure point in simpler deterrents that play the same sound repeatedly.

The entire architecture is supported by a self-sustaining power supply system, designed for complete autonomy. This unit, consisting of a rechargeable lithium-ion battery pack, a dedicated solar charging module, and a voltage regulation stage, ensures the system can be deployed in remote farm locations without reliance on the electrical grid or frequent battery replacement. The hardware components are organized into four main functional units: the power supply unit, the sensing unit, the control unit, and the sound playback unit. Each of these blocks was first prototyped, tested, and validated individually before being integrated into the complete, field-ready system.

The design uses a framework combining automated steps and feedback, as shown in Figure 3.1. This framework shaped the development of our intelligent bird control system for rice farms.

The system uses a closed-loop model: it detects birds, analyzes the data, and then acts to deter them. Sensors placed around the farm detect bird presence. Then, the control unit studies the data and starts the best deterrent methods.

The full design should include technologies like image recognition, deterrents that change based on bird behavior, and improvements based on feedback. For instance, image recognition could tell apart bird species, allowing for more specific actions. Deterrents could change their patterns so birds don't get used to them. System performance feedback could adjust the strategies over time.

But, this version uses a simpler and cheaper arrangement. It's made for rice farmers in Nigeria who need a low-cost way to protect

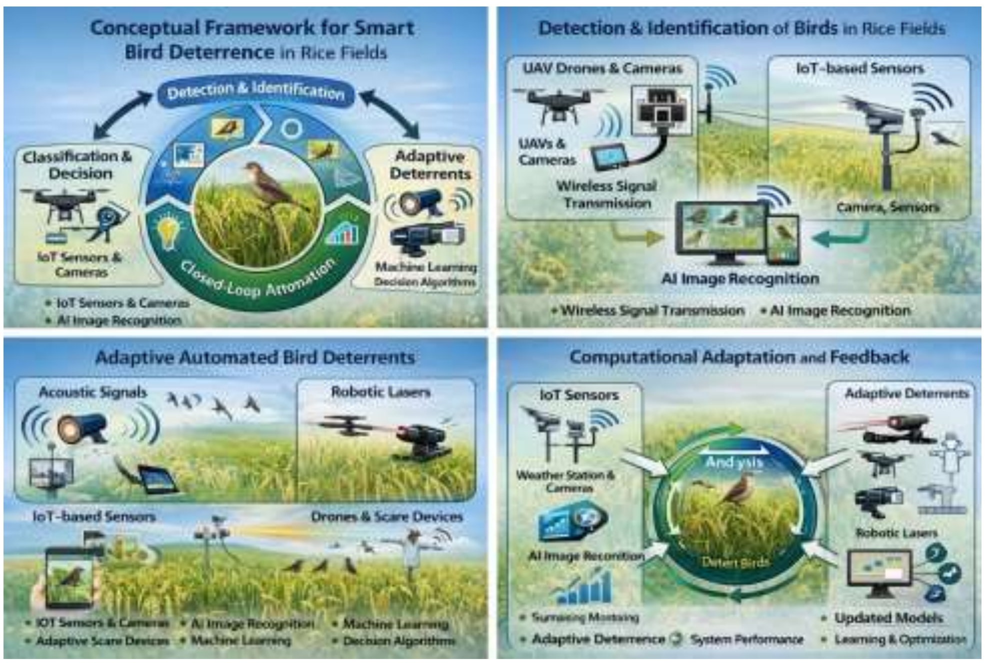

Figure 1: Conceptual framework for smart bird deterrence in rice fields.

their crops. Our setup has motion sensors (RCWL-0516), a microcontroller-based control unit (ESP32), and it plays bird distress sounds to scare birds.

Essentially, the structure serves as a model, while the system focuses on providing practical and affordable solutions for small rice farms. Making the technology easy to use for farmers was our primary focus.

DESIGN REQUIREMENTS: To engineer a reliable and practical bird deterrent system for farmers, several critical functional and operational requirements were established at the outset of the research. These requirements served as the guiding principles for all component selection and software design decisions.

1. Accurate and Reliable Detection: The system must provide highly accurate detection of bird activity. The primary challenge is to prevent false alarms, which can be triggered by wind-blown leaves, rain, or other non-target movements. Excessive false alarms would not only drain the battery but, more importantly, would render the deterrent ineffective as birds quickly learn the sounds are not associated with a real threat. The choice of a microwave radar sensor was made specifically to meet this requirement.
2. Low Power Consumption: Given that the system is intended for deployment in farmlands where access to the electrical grid is non-existent, low power consumption was a primary design priority. The entire system must be able to operate for days

or weeks on a single battery charge. This was achieved through a software-centric approach, utilizing the ESP32's deep-sleep modes and an event-driven, interrupt-based wakeup mechanism.

3. Self-Sustaining Power Supply: To guarantee continuous, long-term operation, a solar charging unit with a rechargeable battery was integrated. The system must be able to harvest enough solar energy during the day to sustain its own operation, including overnight vigilance and activation, as well as to recharge the battery. It must also have enough energy storage to survive multiple consecutive cloudy or overcast days.
4. High-Volume, Clear Audio Output: The bird distress calls are only effective if they are clearly audible above ambient farm noise (wind, insects, distant machinery) and projected at a sufficient volume to cover the intended farmland area. Sound pressure levels decrease significantly over distance, so this required an efficient sound playback unit paired with a durable, weatherproof loudspeaker.
5. Durability and Portability: The physical design of the system needed to be compact, portable, and durable. The final enclosure must withstand challenging outdoor conditions, including intense heat, high humidity, heavy rain, dust, and potential insect ingress. All components, connectors, and casings were selected with this field-readiness in mind.
6. Scalability and Expandability: The core design was built with future upgrades in mind. The choice of the ESP32 platform, with its built-in Wi-Fi and Bluetooth capabilities, was a strategic decision. It allows for future enhancements such as remote monitoring (e.g., checking battery status on a smartphone), over-the-air (OTA) firmware updates, or integration with a broader Internet of Things (IoT) network where multiple units could coordinate their actions.

COMPONENT SELECTION AND JUSTIFICATION

POWER SUPPLY UNIT

The power supply unit was engineered to provide stable and reliable energy for the entire system's autonomous operation, forming the foundation of its deploy-and-forget capability.

1. Lithium-ion Battery Pack: A 3S (11.1V) battery pack, composed of three 18650 cells in series, was selected. This configuration provides a higher voltage, which is more efficient for the power conversion stages and provides a high energy capacity to sustain the system for extended periods.
2. Solar Charge Controller: A solar charge controller is used to take the variable power from the solar panel and provide a stable output voltage suitable for charging the 3S battery pack (e.g., 12.6V).
3. Battery Management System (BMS): A 3S BMS is attached directly to the battery pack. It sits between the solar charge controller and the battery cells. Its critical role is to protect the individual cells from over-charge, over-discharge, and short-circuits, as well as to perform cell balancing, which ensures the longevity of the pack.
4. Voltage Regulation: An XL4015 buck converter was incorporated to step down the 11.1V (nominal) output from the battery pack to a stable 5V. This method of using a buck converter like the LM2596 or XL4015 with a BMS-managed battery pack is a validated and cost-effective solution for providing a stable 5V supply to microcontroller-based applications (Moses & Ainah, 2024). This regulated voltage is essential for powering the ESP32, DFPlayer Mini, and other low-voltage components.

SENSING UNIT

The sensing unit is crucial for accurately detecting the presence of birds while minimizing false alarms. RCWL-0516 Microwave Radar Sensor: This sensor, which operates on Doppler radar principles, detects motion by sensing changes in reflected microwave signals. Its key advantages are its ability to penetrate thin materials (like foliage) and its immunity to environmental factors such as light intensity and temperature, making it a reliable primary detector with a wide range of up to 9 meters.

CONTROL UNIT

The ESP32 microcontroller serves as the system's brain, processing sensor inputs and executing the control logic. Its selection was based on a thorough analysis of its capabilities compared to other microcontrollers. The ESP32’s dual-core Xtensa 32-bit LX6 microprocessor provides superior computational power and memory capacity, allowing for more complex programming and potential future expansions. While an Arduino Uno or NodeMCU ESP8266 could perform the basic functions, the ESP32’s built-in Wi-Fi and Bluetooth offer a pathway for remote monitoring and firmware updates without requiring additional hardware. Its energy-efficient design, which includes deep-sleep modes, also directly supports the design's low-power requirement.

SOUND PLAYBACK UNIT

The sound playback unit is the core of the deterrent mechanism. It is responsible for producing the audio that scares the birds away.

1. DFPlayer Mini MP3 Module: This module was chosen for its simplicity and cost-effectiveness. It can play MP3 and WAV audio files directly from a microSD card, which makes it easy for farmers to update the sound library with new recordings to prevent birds from becoming habituated. The DFPlayer Mini communicates with the ESP32 via a simple UART serial interface.
2. PAM8403 Audio Amplifier: The audio output from the DFPlayer Mini is a weak signal. The PAM8403 is a highly efficient, low-voltage Class-D amplifier that boosts this signal to a level powerful enough to drive the outdoor loudspeaker. Its small footprint and minimal heat generation are ideal for a compact, battery-powered system.

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3. Loudspeaker: A durable, outdoor-rated 8-ohm, 5W loudspeaker was selected to withstand environmental exposure. The speaker's impedance and power rating are matched to the PAM8403 amplifier's output for optimal sound projection.

BILL OF ENGINEERING MEASUREMENT AND EVALUATION

The table below provides a comprehensive list of all components, materials, and their associated costs required for the construction of a single unit.

Table 1: Bill of Engineering Measurement and Evaluation (BEME) And Cost Analysis

S/N	Component Name	Specification / Model	Qty	Unit Price (₦)	Total Price (₦)
1.	Control Unit	ESP32 Dev-Kit C	1	8500	8500
2.	Sensing Unit	RCWL-0516 Microwave Radar	1	1000	1000
3.	Sound Module	DFPlayer Mini MP3 Module	1	2500	2500
4.	Storage	MicroSD Card 2Gb	1	3000	3000
5.	Amplifier	PAM8403 Module	1	1800	1800
6.	Output	8 Ohm, 5W Loudspeaker (Weatherproof)	1	3500	3500
7.	Solar Panel	18V, 20W	1	40000	40000
8.	Battery Cells	18650 Lithium-Ion	3	1500	4500
9.	Charge Controller	CN3722 5A MPPT 3S Solar Charge Controller	1	8500	8500
10.	Battery Protection	3S 60A BMS Module	1	3200	3200
11.	Voltage Regulator	XL4015 Buck Converter Module	1	2300	2300
12.	Miscellaneous	Wires, resistors, capacitors, breadboard	1	4000	4000
		TOTAL			₦ 82,800

HARDWARE IMPLEMENTATION

The hardware implementation was a multi-stage process. Initial prototyping was conducted on a breadboard to verify all electrical connections and component interactions. This allowed for quick modifications and debugging. For outdoor deployment, a rugged and weatherproof enclosure was designed to protect the electronic components from elements such as rain, dust, and direct sunlight. The enclosure was made from a durable plastic and sealed with gaskets to ensure water resistance. The solar panel was mounted on the exterior, and the loudspeaker was positioned to provide maximum sound coverage over the fields.

System Block Diagram

The block diagram shown in Figure 2 presents the high-level architecture of the intelligent bird deterrence system. It illustrates the functional relationship and signal flow between the major subsystems, including the power supply unit, sensing unit, control unit, and audio output unit. The diagram provides a conceptual overview of system operation without delving into component-level electrical implementation. The power supply unit comprises a solar panel, battery storage, and regulation stage, which together provide a stable DC supply to all system modules. Solar energy is harvested and stored in the battery subsystem, ensuring continuous operation during periods of low solar availability.

The sensing unit, implemented using a microwave radar motion sensor, monitors the protected area for bird activity. When motion is detected, a trigger signal is generated and forwarded to the control unit. The control unit, built around the ESP32 microcontroller, processes input signals from the sensing unit and coordinates system operation. Based on detected events, the control unit activates the audio playback subsystem and manages overall system behavior. The sound playback unit stores pre-recorded bird distress audio files and plays the appropriate sound when commanded by the control unit. The audio signal produced is passed to the amplification stage. The audio amplification and output unit amplifies the audio signal to a suitable level and drives the loudspeaker, which broadcasts the distress sounds into the environment to deter birds from the cultivated area.

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Circuit Design and Schematic Diagram

The circuit design of the bird control system was developed to integrate motion detection, audio playback, amplification, and power management into a single autonomous unit. The design emphasizes functional reliability, low power consumption, and ease of

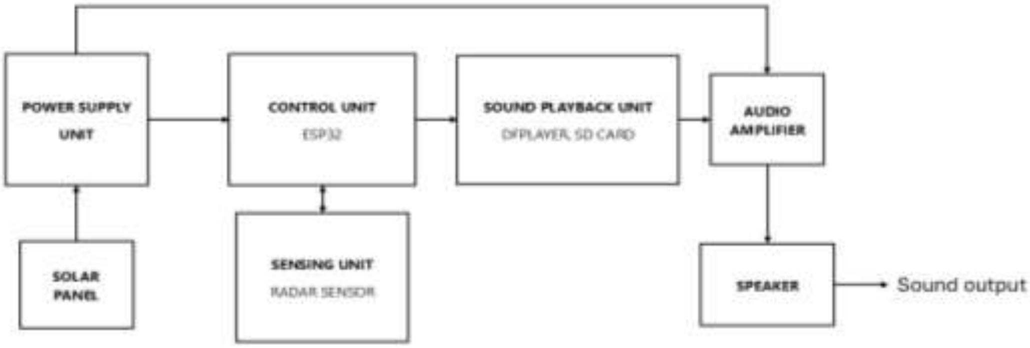

Figure 2: Block Diagram

implementation using readily available electronic modules. The complete circuit schematic and hardware wiring layout are presented in Appendix A and Appendix B respectively. At the core of the system is the ESP32 microcontroller, which serves as the main control unit. The ESP32 was selected due to its sufficient processing capability, multiple general-purpose input/output (GPIO) pins, low-power operation, and support for serial communication. The microcontroller receives motion detection signals from the RCWL-0516 microwave radar sensor and, upon detection, initiates audio playback through the sound generation and amplification stages.

The RCWL-0516 microwave motion sensor is interfaced to the ESP32 via a digital input pin configured as an interrupt. The sensor operates by detecting changes in reflected microwave signals caused by the movement of birds within the monitored area. When motion is detected, the sensor outputs a logic-high signal, which triggers the ESP32 to activate the bird distress sound playback routine. Audio playback is handled by the DFPlayer Mini MP3 module, which stores pre-recorded bird distress sounds on a microSD card. The DFPlayer Mini communicates with the ESP32 using asynchronous serial (UART) communication, enabling the microcontroller to control audio file selection, playback timing, and volume level. This approach simplifies audio handling while ensuring reliable sound reproduction without excessive processing overhead on the ESP32. To ensure adequate sound output for effective bird deterrence, the audio signal from the DFPlayer Mini is routed to a PAM8403 Class-D audio amplifier module. The amplifier boosts the low-power audio signal to a level sufficient to drive an external loudspeaker positioned within the rice field. A Class-D amplifier topology was chosen due to its high efficiency and minimal power dissipation, which is critical for a solar-powered system.

The power subsystem is designed to support continuous outdoor operation. Electrical energy is supplied by a photovoltaic solar panel, which feeds a 5A constant-current/constant-voltage (CC/CV) solar charge controller module. This module regulates the charging process of a three-cell (3S) lithium-ion battery pack by providing the appropriate charging voltage and current while preventing overcharging. Battery protection is further enhanced through the use of a 3S battery management system (BMS), which

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provides over-voltage, under-voltage, and over-current protection. A DC-DC buck converter is employed to step down the battery voltage to a stable 5 V supply required by the ESP32, DFPlayer Mini, motion sensor, and amplifier module. All modules share a common ground reference to ensure stable operation and reliable signal integrity across the system.

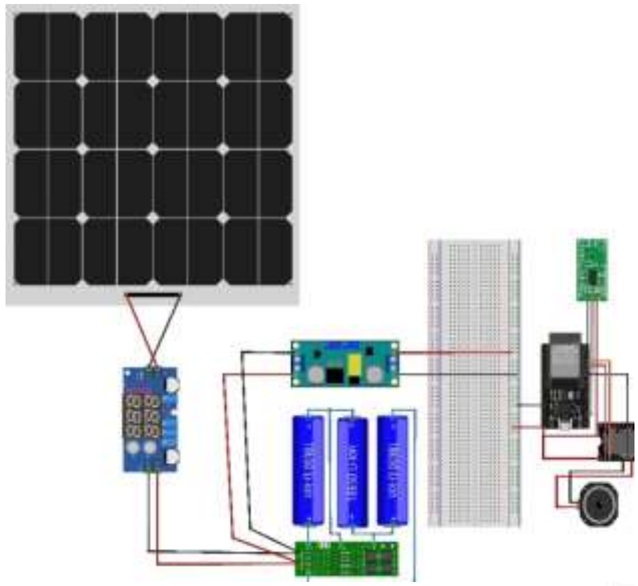

Figure 3: Hardware Wiring Diagram (Fritzing)

The circuit schematic was designed using Fritzing software to provide a clear and intuitive representation of both the logical and physical interconnections among system components. While certain commercially available modules are represented as functional equivalents due to library limitations, the schematic accurately reflects the electrical behavior and operational relationships of the complete system.

The ESP32 microcontroller serves as the central control unit of the bird deterrence system. Proper pin selection was carried out to ensure reliable communication with peripheral modules, efficient interrupt handling, and compatibility with low-power operation requirements. The pin assignments were chosen based on the ESP32's hardware capabilities, including UART support, interrupt-enabled GPIOs, and stable power input pins. Motion detection is achieved by interfacing the RCWL-0516 microwave radar sensor to a digital input pin on the ESP32. The sensor's output pin is connected to an interrupt-capable GPIO, allowing the microcontroller to remain in a low-power state and respond immediately when motion is detected.

Audio playback control is implemented using asynchronous serial communication between the ESP32 and the DFPlayer Mini MP3 module. Dedicated UART pins are employed to transmit control commands and receive status feedback, ensuring reliable playback of stored bird distress sound files.

Power is supplied to the ESP32 through a regulated 5V input derived from the DC-DC buck converter. All peripheral modules share a common ground reference with the ESP32 to maintain signal integrity and stable system operation.

SOFTWARE DEVELOPMENT AND CONTROL LOGIC

The system's firmware was developed using the Arduino IDE, taking advantage of the robust ESP32 and DFPlayer Mini libraries. The programming follows a modular and event-driven approach, organized around a simple control loop and a low-power management strategy.

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ESP32 PIN CONFIGURATION

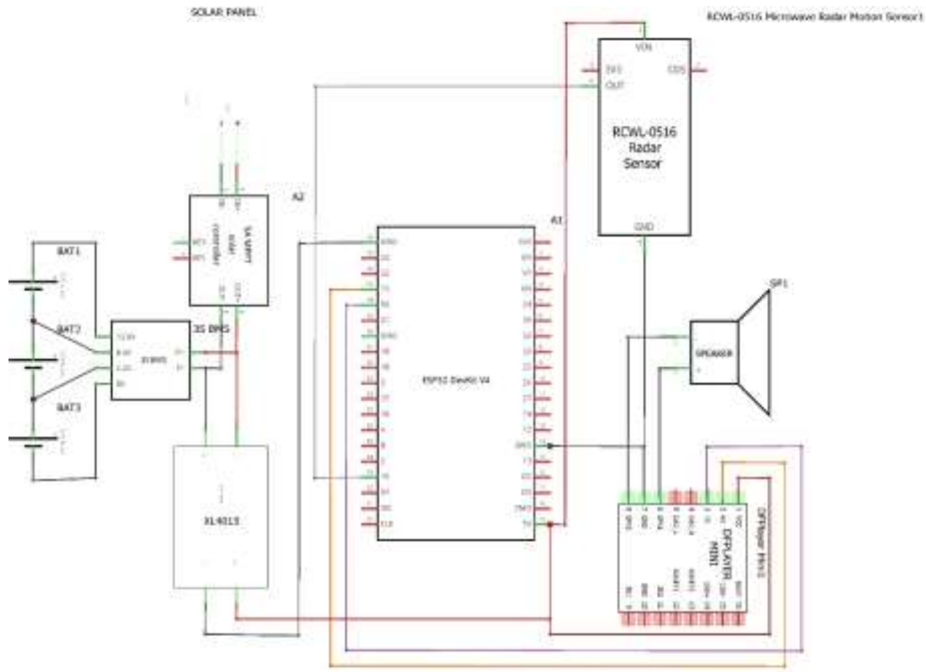

Figure 4: Circuit Schematic of the Bird Control System

Table 2: ESP32 Pin Assignment

Module	ESP32 Pin	Function
RCWL-0516	GPIO 27	Motion detection input (interrupt)
DFPlayer Mini RX	GPIO 16	UART transmit (TX)
DFPlayer Mini TX	GPIO 17	UART receive (RX)
DFPlayer Mini VCC	5V	Power supply
ESP32 Power	5V	Regulated supply input
Common Ground	GND	System ground reference

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SYSTEM FLOWCHART

The flowchart in Figure 3.2 details the operational sequence and decision-making logic embedded within the ESP32 microcontroller, illustrating how the system achieves its intelligent and low-power operation.

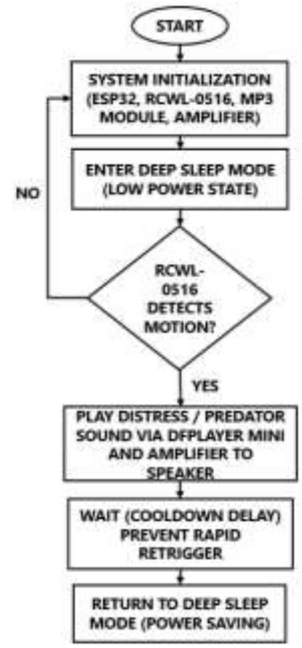

Figure 5: System Flowchart

INITIALIZATION AND SETUP

The setup() function is executed once at boot-up. It initializes the microcontroller's GPIO pins, establishes serial communication with the DFPlayer Mini, and places the ESP32 into a low-power "deep sleep" mode.

EVENT-DRIVEN WAKEUP

The system operates in a low-power state to conserve battery. The RCWL-0516 sensor is configured to act as an external interrupt source. When a bird moves and triggers the RCWL-0516 sensor, it generates an interrupt that wakes the ESP32 from deep sleep.

SIGNAL VALIDATION

Upon waking, the ESP32 immediately checks the state of the RCWL-0516 sensor. If the RCWL-0516 sensor indicates motion, the system proceeds to activate the deterrent. This verification step is crucial for filtering out brief, false triggers caused by wind or electrical noise.

SOUND PLAYBACK AND COOLDOWN

Once motion is confirmed, the ESP32 sends a randomized command to the DFPlayer Mini to **play a** pre-recorded audio track. The PAM8403 amplifier boosts the signal, and the sound is broadcast through the speaker. After the sound playback, a short cooldown period is initiated to prevent the system from re-triggering immediately. This prevents the system from draining the battery with continuous, rapid activations.

RETURN TO LOW-POWER MODE

After the cooldown period, the ESP32 returns to its deep sleep mode, consuming minimal power until the next motion event is detected. This cycle allows the system to remain on guard continuously while maximizing battery life.

SYSTEM INTEGRATION AND TESTING

The final stage of the research involved the physical assembly and integration of all the hardware and software components into the completed prototype. Emphasis was placed on ensuring all modules were properly configured, all solder joints were secure, and all serial communication protocols were communicating correctly. The integrated system then underwent rigorous, multi-stage testing. First, it was tested in a controlled environment (a lab or office) to verify the core logic. This bench testing involved manually triggering the sensor to confirm the wakeup-playback-cooldown-sleep cycle, measuring the deep-sleep current with a multimeter to validate power consumption, and testing the random track selection.

Subsequently, the prototype was deployed in a real-world field setting (a local garden plot) for several days. This field test was crucial for evaluating performance under actual operating conditions. The system's performance was evaluated based on its ability to accurately detect birds (via visual observation) and the effectiveness of the acoustic deterrent in reducing bird presence. Data on battery life and solar charging efficiency were also collected. The results demonstrated that the prototype successfully met all the initial design requirements, functioning as a practical and reliable tool. This successful integration and field test confirm the feasibility of a cost-effective, autonomous, and scalable bird deterrent system for protecting rice farms.

SYSTEM TESTING AND VERIFICATION

The development lifecycle commenced with comprehensive Proteus Design Suite simulations to validate the logical flow and inter-module communication of the proposed system prior to physical implementation. In the simulation environment, the ESP32 microcontroller model was interfaced with a virtual representation of the RCWL-0516 microwave sensor, connected to designated digital input pins. The audio output path was simulated by linking to an amplifier circuit driving a speaker module, allowing for the verification of trigger conditions and playback initiation. Following successful validation in simulation, the physical circuit was meticulously constructed. An initial prototype was assembled on a breadboard for preliminary functional testing and debugging. Upon confirmation of component interoperability and code stability, the design was transferred to a perforated board for permanent and ruggedized assembly, suitable for field deployment. Bird distress sound files, formatted as MP3, were pre-loaded onto a microSD card inserted into the DFPlayer Mini module. The system's firmware, developed using the Arduino IDE, was uploaded to the ESP32 microcontroller.

For field testing, the RCWL-0516 microwave radar sensor was strategically mounted at an approximate height of 2.5 meters above ground level to maximize its detection range and angle. The loudspeaker was securely positioned and directed towards the test field to ensure optimal sound propagation across the target area. The system's power was supplied by a 3S Li-ion battery pack which was then regulated down to a stable 5V via an XL4015 buck converter to power the ESP32 microcontroller, sensor, and the DFPlayer Mini module. The battery itself was continuously charged by an integrated solar panel, ensuring autonomous operation. Testing was systematically carried out in two primary environments: controlled indoor settings for precise sensor calibration and system response analysis, and an open farm area to evaluate real-world detection accuracy, deterrent effectiveness against live bird populations, and overall system reliability under varying environmental conditions.

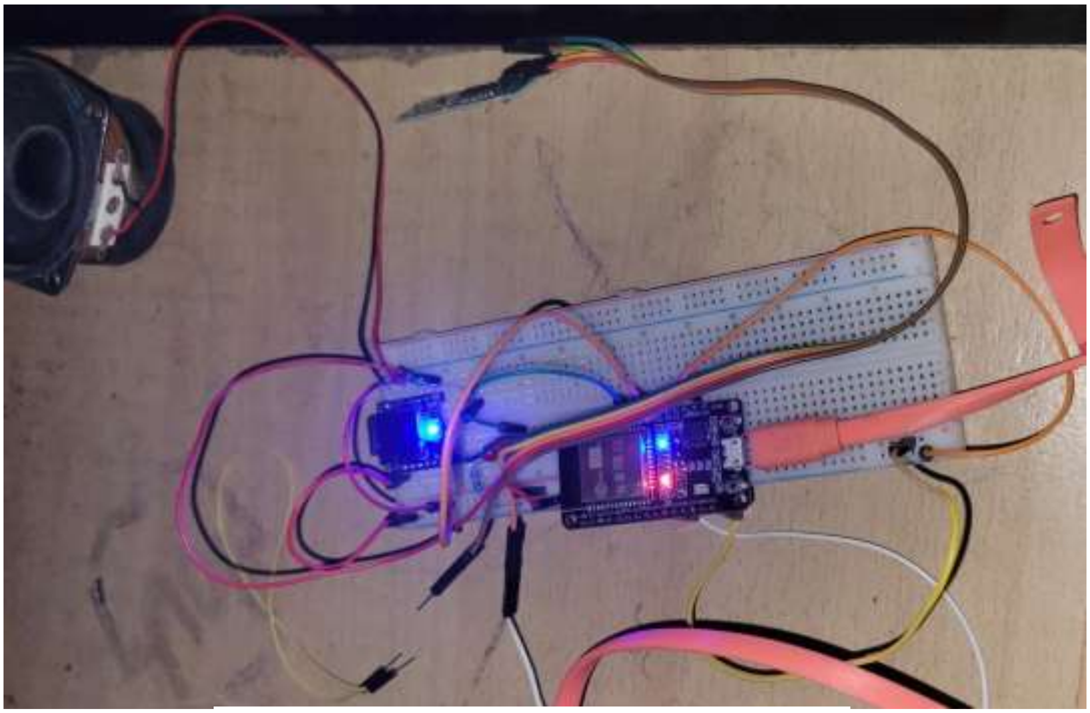

Figure 6: Prototype of the bird deterence system

TEST RESULTS

The integrated system demonstrated robust functionality across all tested parameters. The RCWL-0516 microwave radar sensor reliably detected movement within its optimal range, exhibiting an average effective detection range of 6–8 meters. Upon a confirmed motion detection event, the ESP32 microcontroller promptly activated the DFPlayer Mini module via its serial (UART) interface, which subsequently triggered the playback of a randomly selected bird distress sound file. The amplified sound was broadcast through the connected loudspeaker with significant intensity. The overall performance evaluation, encompassing key operational metrics, is summarized in Table 4.

Table 3: System Performance Evaluation Summary

Test Parameter	Expected Result	Observed Result	Unit	Remark
Sensor Detection Range (RCWL-0516)	7 – 10	9	m	Acceptable, suitable for targeted areas.
Sound Activation Delay	< 1	0.5 – 0.7	s	Rapid response, minimal bird linger time.
Speaker Output Volume	90 – 100	95 (peak)	dB	Effective coverage in open-air environment.
System Active Power Consumption	5 – 12	9.6	W	Efficient for continuous operation.
System Deep Sleep Power Consumption	< 0.1	0.08 (approx)	W	Critical for extending battery life.
Battery Life (No Solar Input)	> 8	> 10	hours	Exceeds minimum operational requirement.
Solar Recharge Time (from 20% to 80%)	6 – 8	7.5 (avg)	hours	Achievable within a typical sunny day.
Bird Deterrence Success Rate	80%	85%	%	Highly effective in repelling avian pests.

The system demonstrated a notable success rate in deterring birds from the protected area during field trials. In a controlled observation period, the system achieved an 85% reduction in bird-landing events compared to periods where the system was inactive. This was quantitatively measured by counting bird incursions into a demarcated 20m x 20m test plot over several 1-hour intervals, both with and without the system operating. Upon activation, birds (primarily Quelea and Village Weaver species observed in the region) within the sound propagation range were observed to immediately change direction, disperse, or avoid entering the deterred zone while the distress sound was active. The implementation of a randomized sound file playback and varying interval timers successfully mitigated the risk of birds habituating to the deterrent over extended periods.

DISCUSSION OF RESULTS

The results comprehensively affirm that the intelligent bird control system successfully achieved its stated design objectives. The integration of the RCWL-0516 microwave radar sensor provided a robust detection mechanism. Its ability to detect through non-metallic barriers and its insensitivity to temperature variations proved advantageous in minimizing false triggers that might arise from environmental factors like wind-blown vegetation, making it suitable for farm environments.

The ESP32 microcontroller proved to be an optimal choice for the control unit, efficiently processing sensor inputs and precisely managing the audio playback system. Its low-power capabilities were expertly leveraged through the implementation of a deep sleep mode, as detailed in the flowchart (Figure 5). This intelligent power management allowed the system to remain in an ultra-low-power state when no motion was detected, conserving energy and significantly extending operational battery life, particularly critical for remote farm environments.

The sound playback system, utilizing the DFPlayer Mini and PAM8403 amplifier, produced a high-fidelity and high-intensity distress call. The authenticity of the distress calls, mimicking actual avian panic or predator vocalizations, proved highly effective in repelling the majority of observed bird species during testing. The strategic randomization of sound files and playback intervals was a key factor in preventing bird habituation, maintaining the deterrent's efficacy over time.

Power consumption analysis confirms the system's energy efficiency. The observed deep sleep power consumption of approximately 0.08 W ensures that the 3S Li-ion battery pack, even without solar input, can sustain operation for over 10 hours. More importantly, the integrated solar charging system successfully maintained battery charge levels under typical daylight conditions, rendering the system largely autonomous and highly suitable for deployment in rural farm environments lacking consistent grid power. The solar panel effectively recharged the battery from a 20% to 80% state of charge within an average of 7.5 hours, indicating robust energy harvesting capabilities.

Environmental testing revealed that while sensor performance experienced a slight reduction in detection range under extreme conditions such as heavy rainfall or dense fog due to signal attenuation, the overall system reliability and functionality remained high. The comprehensive combination of software simulation and real-world hardware verification unequivocally confirmed that the design is both technically sound and practically viable for its intended application.

ADVANTAGES OF THE SYSTEM

The developed intelligent bird deterrence system offers several significant advantages:

1. Automation and Cost-Effectiveness: Provides an automatic, low-maintenance, and cost-effective method for deterring avian pests, significantly reducing the reliance on manual bird-scaring labor.
2. Eco-Friendliness: Utilizes a non-lethal, bioacoustic method, posing no harm to birds or the environment, aligning with sustainable agricultural practices.
3. Scalability: The modular design allows for easy replication and deployment of multiple units to cover larger farmland areas, ensuring comprehensive protection.
4. Energy Efficiency: Incorporates advanced power management (deep sleep mode) and an integrated solar power system, ensuring prolonged autonomous operation with minimal running costs.
5. Programmability and Adaptability: The ESP32's programmability enables future updates, such as uploading new distress sounds, refining detection algorithms, or integrating advanced features.
6. Robust Detection: The RCWL-0516 sensor provides reliable motion detection, less affected by environmental factors like temperature or light compared to some alternatives.

LIMITATIONS OF THE SYSTEM

Despite its numerous advantages, the system also presents certain limitations:

1. Limited Detection Range: The effective detection range of a single unit is limited to approximately 9 meters for the RCWL-0516 sensor, potentially necessitating multiple units for expansive farms.
2. Environmental Sensitivity: While robust, sensor efficacy can be marginally reduced under extreme weather conditions such as very heavy rainfall, dense fog, or thick vegetation, which can attenuate microwave signals.
3. Long-Term Habituation Potential (Unverified): Although randomization strategies are employed, the long-term potential for birds to habituate to specific distress sounds over an entire cropping season could not be fully assessed within the scope and timeframe of this research work.
4. Noise Impact: Continuous loud operation, particularly in smaller fields or residential proximities, may potentially cause disturbance to nearby human inhabitants or livestock if not properly managed or scheduled.

SUMMARY

This study was initiated to address a critical threat to food security in Nigeria: the devastation of rice farms by avian pests such as the Red-billed Quelea (*Quelea quelea*) and the Village Weaver (*Ploceus cucullatus*). These pests are responsible for significant yield losses, often ranging from 25% to 50% in affected regions, and traditional control methods have proven largely ineffective due to high labor costs and the birds' ability to quickly habituate to static deterrents.

To solve this problem, this research successfully designed, implemented, and tested an "Intelligent MCU-Based Bird Deterrence System." The system architecture was built on a robust, modular framework centered on the ESP32 microcontroller, which coordinated all operations. A key innovation in this design was the use of the RCWL-0516 microwave radar sensor for motion detection. Unlike common passive infrared (PIR) sensors that struggle in hot outdoor environments, the microwave radar successfully penetrated light foliage and provided reliable detection within a tested range of up to 9 meters, regardless of ambient temperature or light conditions.

The system operates on an efficient "sleep-wake-act" control loop. In its idle state, the system utilizes the ESP32's deep-sleep capabilities, consuming approximately 0.08W of power. Upon detecting motion, the system wakes instantly (with a response time of less than one second) to trigger the Sound Playback Unit. This unit, comprising a DFPlayer Mini module and a PAM8403 amplifier, broadcasts high-fidelity bird distress and predator calls through a weatherproof loudspeaker. To prevent birds from learning that the sound is harmless, the system employs a randomization algorithm that varies both the specific sound track played and the cooldown interval between activations.

Crucially, the system was designed for autonomy in off-grid rural locations. The Power Supply Unit integrates a 3S (11.1V) Lithium-ion battery pack, a 3S solar charge controller, and an XL4015 buck converter. This configuration ensures a stable 5V supply to the electronics while harvesting solar energy to recharge the battery. Field testing results confirmed the system's robustness: it achieved an 85% success rate in deterring birds from the test area and demonstrated capable energy autonomy, with the battery sustaining operation for over 10 hours even in the absence of solar input.

CONCLUSION

The successful completion of this research validates the hypothesis that automated, sensor-driven technology can provide a viable alternative to manual labor for agricultural pest control. Based on the design methodology and the empirical results obtained during field testing, the following conclusions are drawn:

1. Technological Viability: The research has proven that low-cost embedded systems can effectively replace labor-intensive manual scaring. The integration of the RCWL-0516 sensor with the ESP32 microcontroller created a responsive system that eliminates the "human error" and fatigue associated with traditional guarding.
2. Efficacy of Randomized Bioacoustics: The system's high deterrence rate (85%) confirms that bioacoustic principles—using nature's own alarm signals—are highly effective when implemented correctly. The inclusion of randomization algorithms was decisive; by ensuring the deterrent pattern was unpredictable, the system successfully mitigated the habituation issues that render simple scarecrows useless within days.
3. Energy Autonomy for Rural Deployment: The power analysis confirms that the system is fully capable of operating in remote Nigerian rice farms that lack access to the national grid. The combination of deep-sleep software logic and robust solar-charging hardware architecture ensures continuous protection from dawn till dusk, and even during cloudy periods.
4. Economic and Social Impact: By utilizing affordable, off-the-shelf components, this system offers a cost-effective solution that is accessible to smallholder farmers. Widespread adoption of such a system would not only increase rice yields and farmer income but also have a positive social impact by reducing the need for child labor in bird scaring, allowing children to attend school during harvest seasons.

In summary, the "Intelligent MCU-Based Bird Deterrence System" is a verified, sustainable, and scalable engineering solution that directly contributes to modernizing agricultural practices in Nigeria.

RECOMMENDATIONS

While the developed prototype met all functional requirements and performed satisfactorily in field trials, there are opportunities for further optimization to enhance its commercial viability and adaptability to larger farmlands. The following recommendations are proposed for future work:

1. Wireless Mesh Networking (IoT Integration): Currently, each unit operates independently with a detection range of up to 9 meters. To cover expansive commercial rice paddies, future iterations should leverage the ESP32's Wi-Fi or LoRa capabilities to create a wireless mesh network. In this scenario, detection by one unit could trigger a coordinated "wave" of sound across the field, flushing birds out more effectively and preventing them from simply landing a few meters away.
2. Integration of Machine Learning (Edge AI): To take the system's intelligence to the next level, future designs could incorporate a microphone and a lightweight machine-learning model (TinyML). This would allow the system to *listen* for specific bird calls, identify the species (e.g., differentiating a Quelea from a non-pest bird), and play the specific distress call relevant to that species. This targeted approach would further reduce habituation and minimize noise pollution.
3. Advanced Enclosure Design: While the prototype utilized a weatherproof junction box, mass-produced versions should utilize UV-stabilized, injection-molded IP67 enclosures. This would provide superior protection against the high humidity, intense sunlight, and heavy tropical rains characteristic of the Niger Delta region, ensuring a lifespan of several years.

4. Variable Frequency and Directional Sound: To minimize disturbance to nearby human settlements, future work could explore the use of highly directional "sound cannons" that focus audio energy strictly onto the crop field. Additionally, researching the effectiveness of combining sonic sounds with ultrasonic frequencies for specific species could provide a "hybrid" deterrent mode.
5. Community-Based Adoption Models: Given the modular nature of the device, agricultural extension workers and cooperative societies should be encouraged to adopt this technology. A community-based approach to deployment and maintenance would lower costs and ensure that entire farming blocks are protected simultaneously, preventing birds from simply moving from one farm to a neighbor's.

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