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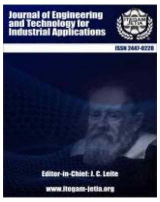

RESEARCH ARTICLE OPEN ACCESS

DEVELOPMENT OF A MICROCONTROLLER-BASED AUTOMATED PEST CONTROL SPRAYING SYSTEM

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ABSTRACT

This study aimed to develop and evaluate an automatic pest control spraying system using locally available materials, designed to enhance precision in pest management while minimizing human exposure to pesticides and reducing environmental impact. The system was tested on a plant bed to assess its efficiency, effectiveness, sensitivity, and economic viability, using parameters such as payback period, internal rate of return (IRR), and benefit-cost ratio (BCR). Employing a descriptive-experimental design, the prototype automatically detected pests and sprayed pesticides only at the detected location. The system consisted of a 230V AC source, digital time relay switch, Arduino Uno, PIR sensors, relay module, solenoid valve, and pump. Results showed that larger sample sizes improved effectiveness and sensitivity. The pump and solenoid valve efficiencies were 95.49% and 93.46%, respectively, while sensor efficiencies were 75.00%, 66.67%, and 29.17% for caterpillar, cockroach, and grasshopper detection. Economic analysis indicated a payback period of 8 months and 5 days, an IRR of 39.46%, and a BCR of 1.41, signifying strong financial feasibility.

I. INTRODUCTION

Food plays a fundamental role in human development, health, and economic growth, where agriculture serves as the backbone of sustainable food systems. Agriculture provides eco-friendly, renewable crops and animal products that ensure food security and rural development. Globally, value-added output in agriculture, forestry, and fishing increased by approximately 84% between 2000 and 2021, reaching about USD 3.7 trillion. Asia accounted for 65% of this growth, emphasizing the region's dominant contribution to global agricultural expansion. Moreover, the global production of primary crops reached 9.5 billion tons in 2021, reflecting a 54% increase compared to 2000. Despite this growth, the share of agriculture in global GDP has remained around 4% since 2000, underlining the sector's stable yet vital role in the global economy [1]. In the Philippines, agriculture remains a key contributor to both the economy and livelihoods.

During the first quarter of 2023, the value of agricultural and fishery production—measured at constant 2018 prices—reached PhP 428.69 billion, an annual increase of 2.1%. Crop production accounted for PhP 247.77 billion or 57.8% of the total output [2]. Approximately 25–30% of Filipinos depend directly on agriculture for their livelihood, contributing nearly 10% to the gross national product [3]. However, recent crises such as the COVID-19 pandemic and climate change have disrupted global agricultural productivity [4]. Climate-related challenges—rising temperatures, erratic rainfall, and frequent extreme weather—have led to pest outbreaks, crop failures, and declining yields [5-9]. Empirical analyses indicate that global agricultural total factor productivity has already declined by around 21% since 1961 due to anthropogenic climate change, with developing regions experiencing the greatest losses [7].

Pest infestation continues to pose serious threats to agricultural productivity [10]. Studies emphasize that pest and disease control is critical for yield optimization and crop sustainability [8], [11], [12]. Consequently, pesticide use has become a primary pest management strategy [5]. Between 2000 and 2021, global pesticide use increased by 62%, with Asia contributing 28% of the total [1]. The use of pesticides enhances crop protection and yield [5], [8], [12-14]; however, excessive and unsafe application has raised significant health and environmental concerns [8],[12-15]. Prolonged pesticide exposure is linked to acute symptoms such as dizziness, nausea, and diarrhea, and chronic illnesses including cancer, endocrine disruption, and neurological disorders [14-16]. Furthermore, pesticides contaminate soil and water, harming beneficial organisms and disrupting ecological balance [12-16].

Farmers face additional challenges in pest control at night, where most traditional pest monitoring and spraying methods are limited. Manual pesticide application remains labor-intensive, time-consuming, and often inefficient, leading to inconsistent coverage and increased health risks for workers [8], [12], [17]. To address these limitations, the National Crop Protection Center (NCPC) has promoted research on integrated pest management and sustainable pest control systems [4]. The integration of new innovative technologies is required [8]—such as automated spraying systems, digital sensors, and Internet of Things (IoT)-based pest detection [17], [18], [10]—has been shown to improve productivity, reduce labor requirements, and enhance sustainability in agriculture [17], [18], [9]. Recent findings indicate that digital agriculture improves smallholder farmers' welfare by up to 71.25%, with pest management as one of the key areas of benefit [19].

In this context, developing an automated pest control spraying system designed to detect and repel pests can serve as an innovative solution to optimize yields and safeguard worker health [20]. The proposed system uses passive infrared (PIR) sensors to detect pests, automatically sprays pesticide in targeted areas, and allows programmable timing for spraying cycles. This automation reduces direct pesticide exposure, lowers labor requirements, and ensures more precise pest control. Such technology supports sustainable and smart farming practices that increase agricultural productivity while minimizing environmental and health risks. Specifically, this study aims to analyze existing manual pesticide application in terms of pest types, labor, and costs; design and fabricate an automatic spraying system; test its performance in terms of effectiveness, sensitivity, and efficiency; and assess its economic viability for smallholder farmers in the Philippines.

II. MATERIALS AND METHODS

II.1 SYSTEM AND DESIGN DESCRIPTION

The automated pest control spraying system integrates several key components: a pest detection mechanism, a programmable processing unit, a spraying mechanism, a power supply, and a converter. The pest detection mechanism utilizes Passive Infrared (PIR) sensors strategically positioned along the plant bed to detect motion caused by pest activity [20]. When movement is detected, the sensors send digital signals to the programmable processing unit for data processing and response coordination. This detection approach aligns with recent advances in precision agriculture, where networks of low-cost passive infrared (PIR) sensors and vision-based cameras are increasingly combined with IoT telemetry and machine-learning models to deliver real-time pest monitoring and automated field responses [20], [21], [10].

The programmable processing unit utilizes a shielded Arduino Uno board that handles sensor inputs and transmits control signals to relay-based actuators, ensuring timely and efficient system operation. This microcontroller-based architecture has been widely adopted in agricultural automation applications because of its affordability, adaptability, and dependable integration with diverse sensor arrays and wireless modules, enabling real-time monitoring and control of field conditions [20], [22], [23]. The relay-based switching mechanism, comprising a digital timer relay and an 8-channel relay module, electronically opens and closes circuits to control the activation of the PIR sensors and diaphragm pump. This modular relay configuration is essential for ensuring system scalability, allowing independent timing and sequencing of spray operations, and supporting flexible automation in diverse field conditions [22-24].

The spraying mechanism integrates solenoid valves, diaphragm pumps, an array of pipes, and misting nozzles to ensure the precise dispersion of organic pesticides. The solenoid valve regulates the flow of fluid, while the diaphragm pump transfers pesticide solutions through the connected pipeline to misting nozzles that deliver fine droplets uniformly across plant surfaces. This mechanism mirrors current trends in precision misting and controlled fluid delivery systems, which enhance pesticide utilization efficiency and minimize environmental contamination [20], [25], [26]. The power system comprises a 12V DC source linked to a 230V AC supply, with a converter reducing voltage to 5V DC to power the Arduino unit and associated sensors—consistent with common configurations in automated agricultural systems emphasizing energy efficiency and portability [20], [23], [27].

II.2 DESIGN AND FABRICATION PROCEDURES

During the design and fabrication phase, PIR sensors were installed at one-meter intervals along the plant bed to ensure uniform detection coverage. A functional prototype integrating sensors, pumps, and actuators was developed following specified design parameters. The sensors were calibrated to detect pest movements accurately within their assigned detection zones. Controlled experiments were conducted to assess sensor performance and system responsiveness under varying environmental conditions such as wind and light levels. This systematic approach to calibration and prototype validation is aligned with best practices in smart agricultural device testing and sensor reliability evaluation [28], [29]. Data from sensor readings, pump performance, and system response were analyzed to identify operational trends, ensuring that threshold values and pump discharge rates matched optimal pesticide dispersion performance. Enhancements were implemented based on performance feedback, refining the control algorithms and sensor sensitivity thresholds to achieve consistent accuracy and reliability.

II.3 DATA COLLECTION PROCEDURES

The performance of the automated pest control spraying system was assessed based on three primary criteria: effectivity, sensitivity, and efficiency. Effectivity was determined by simulating pest detection through three trials under varying environmental conditions, measuring the effective detection range of sensors across five distance intervals (0.5–4 meters). Sensitivity was evaluated by calculating the time lag between pest detection and system response, offering a quantitative measure of the controller's performance at different distances. Efficiency analyses covered solenoid valve, sensor, and pump operations. For solenoid valves, efficiency was defined as the ratio of actual to theoretical flow rates, expressed as a percentage. Sensor efficiency represented the ratio between maximum detection range and design specification, while pump efficiency was calculated as the ratio of actual discharge to designed output. Such performance measurement techniques are consistent with engineering testing methodologies used in automated irrigation and spraying systems [30], [31].

II.4 DATA ANALYSIS PROCEDURES

Collected data were analyzed using descriptive statistics such as frequency counts, arithmetic means, and averages to determine operational consistency. Cost-benefit analysis (CBA) was applied to assess economic viability, using metrics such as Benefit-Cost Ratio (BCR), Payback Period (PP), and Internal Rate of Return (IRR). The BCR compared annual benefits with total investment, while PP evaluated the duration required to recover capital costs. The IRR estimated the annualized profitability of the system. These economic indicators align with standard frameworks for evaluating automation technologies in sustainable farming and agri-engineering [22], [31], [32]. By combining technical and economic analyses, the study ensured that the system design was not only functionally efficient but also financially feasible for agricultural deployment.

III. RESULTS AND DISCUSSIONS

III.1 PEST PREVALENCE IN THE AREA

Table 1 presents the mean rates of pest encounters among workers in the study area. The findings indicate that grasshoppers (M = 4.67) and cockroaches (M = 4.33) were the most frequently encountered pests, classified as Very Highly Encountered. Caterpillars (M = 4.00) were Highly Encountered, while ants (M = 2.00) were Encountered and flies (M = 1.33) were the Least Encountered. These results suggest that grasshoppers and cockroaches pose the most significant threats to crop productivity within the observed agricultural environment. The high frequency of grasshoppers and cockroaches supports global trends where these pests are among the most destructive to agricultural productivity, particularly in tropical and humid environments [33]. Grasshopper species commonly flourish in open, sun-lit vegetative landscapes—consuming foliage, pods, and developing grains across a broad spectrum of crops [34].

In contrast, cockroach populations find ideal conditions in moist, shaded micro-habitats (such as under crop residues or in harvesting/storage structures) and frequently act as post-harvest contaminants—penetrating stored commodity stacks, degrading grain quality, and reducing market value [35]. The dominance of grasshoppers and cockroaches implies that pest control systems in the region should prioritize the detection and mitigation of these species [34], [35]. Automated pest management systems, equipped with motion and infrared sensors, can be fine-tuned based on the behavioral characteristics of these pests [21], [36]. Therefore, identifying the pest prevalence provides a strong foundation for designing an efficient and species-targeted automated pest control spraying system.

Table 1: Prevalent pest in the area.

Pest	Mean	Interpretation
Grasshopper	4.67	Very Highly Encountered
Cockroach	4.33	Very Highly Encountered
Caterpillar	4.00	Highly Encountered
Ants	2.00	Encountered
Fly	1.33	Least Encountered

Source: Authors, (2026).

II.2 DESIGN OF THE SYSTEM

Figure 1 to 4 presents the developed system comprised five major components: (1) pest detection mechanism using Passive Infrared (PIR) sensors; (2) programmable processing unit utilizing an Arduino Uno microcontroller; (3) relay-based switching system for activation and deactivation of components; (4) spraying mechanism integrating a solenoid valve, diaphragm pump, and misting nozzles; and (5) a power supply system converting 12V DC to 5V DC. The physical arrangement, as depicted in Figure 1 to Figure 5, demonstrated a well-integrated design ensuring coordinated functionality between detection and actuation modules. The PIR sensors were installed at one-meter intervals along the plant bed to ensure consistent coverage. When pests were detected, the Arduino processed the signal and triggered the relay system, which controlled the solenoid valve and pump.

The misting nozzles sprayed the organic pesticide in a fine distribution pattern, effectively targeting detected pests. Such automation reduces labor intensity [23], [37], [38] and chemical wastage compared to manual spraying [37], [38]. The modular configuration allows scalability and easy maintenance. Previous studies have demonstrated that sensor- and IoT-based pest management systems can reduce pesticide use by around 30–45% while maintaining pest control efficiency [39-41]. The structural integration of detection, processing, and spraying modules validates the design as functionally cohesive and sustainable. It provides a viable technological advancement for small-scale farmers, promoting safer and more efficient pesticide application. The system's design also aligns with smart agriculture frameworks emphasizing automation, precision, and environmental protection [42].

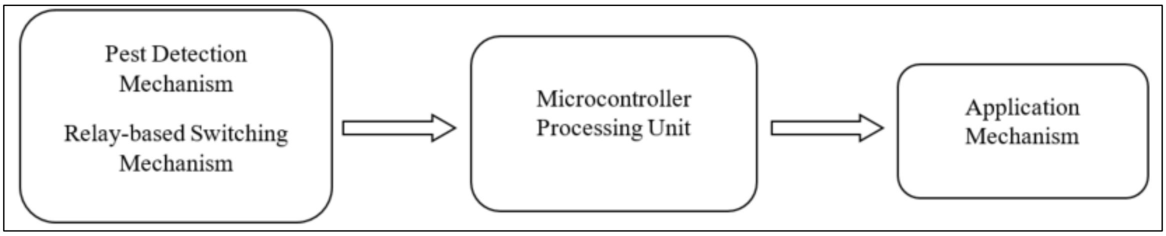

Figure 1: Block Diagram of the Automated Pest Control Spraying System.
Source: Authors, (2026).

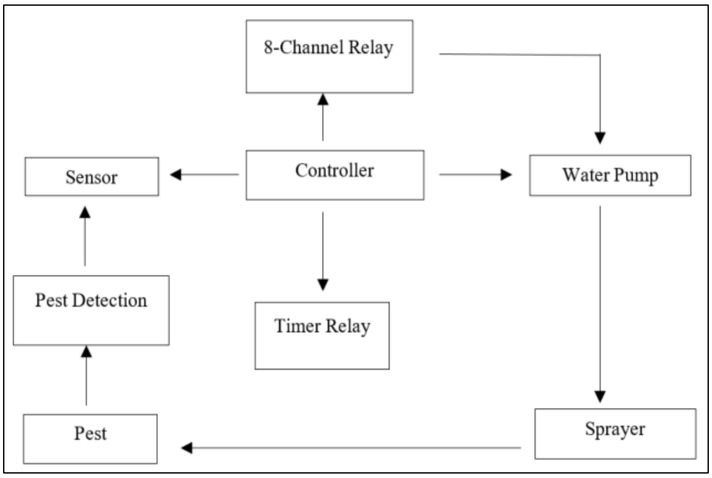

Figure 2: Operational Flow of the Automated Pest Control Spraying System.
Source: Authors, (2026).

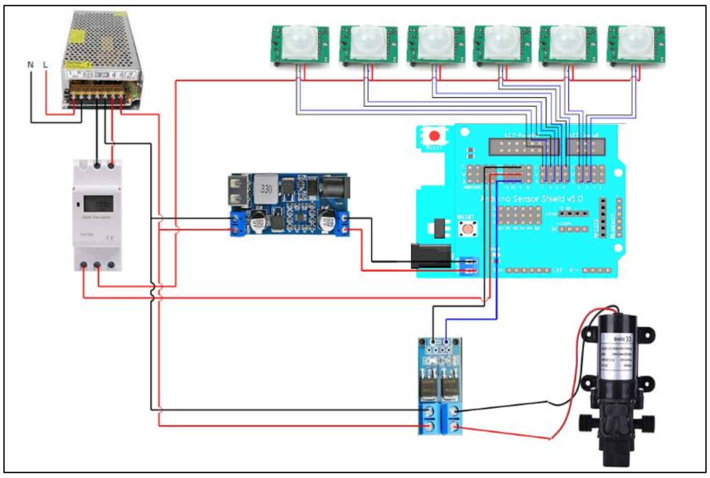

Figure 3: Circuit Diagram of the Automated Pest Control Spraying System.
Source: Authors, (2026).

Figure 4: Fabrication of the Automated Pest Control Spraying System.
Source: Authors, (2026).

III.3 PERFORMANCE ANALYSIS

III.3.1 Effectivity

As reflected in Table 2, “Y” indicates that the pest was detected at the specified distance, while “N” indicates that the pest was not detected at the specified distance. Sensor performance trials indicated that caterpillars were detected up to 3.00 meters, cockroaches up to 2.67 meters, and grasshoppers up to 1.17 meters. Detection distance decreased with smaller insect size and faster movement. Environmental factors, such as wind, slightly reduced sensor accuracy, particularly at greater distances.The results confirm that PIR sensors are more effective at detecting larger and slower-moving insects due to their stronger infrared signatures [43].

Similar findings were reported by [43], who noted that detectability drops significantly for smaller arthropods with infrared sensors alone. Detection distance variability aligns with research by [44], suggesting that hybrid sensors combining infrared and visual technologies improve small-pest detection accuracy. The data validate the system’s capability for pest detection but also reveal limitations for smaller or faster pests. These results highlight the need for sensor calibration or multi-sensor integration for enhanced adaptability. Despite environmental challenges, the sensor’s range remains adequate for operational field use, confirming the system’s practical applicability.

Table 2: Actual Effectivity of the System.

Pest	**Effective Distance**				
Grass hopper	**0.5m**	**1m**	**2m**	**3m**	**4m**
Trial 1	Y	Y	N	N	N
Trial 2	Y	N	N	N	N
Trial 3	Y	Y	Y	N	N
Cockroach					
Trial 1	Y	Y	Y	Y	N
Trial 2	Y	Y	Y	Y	N
Trial 3	Y	Y	Y	N	N
Caterpillar					
Trial 1	Y	Y	Y	Y	N
Trial 2	Y	Y	Y	Y	N
Trial 3	Y	Y	Y	Y	N

Source: Authors, (2026).

III.3.2 Sensitivity

Table 3 presents the average response time of the sensors varied with pest size and distance. Larger pests such as caterpillars triggered the system within approximately 5.5 to 8.7 seconds, while smaller and faster pests like grasshoppers required 6.6 to 14.3 seconds for detection. Detection was faster at shorter distances and under stable environmental conditions. The variation in response time indicates that PIR sensor sensitivity depends on the infrared intensity emitted by the pest and environmental stability. Similar findings were reported by [45], who explained that motion-based sensors in arable crops exhibit variable responsiveness under changing ambient conditions.

Wind and temperature fluctuations can cause false signals or delayed responses—an effect supported by [46], who emphasize the importance of calibrating sensor thresholds for compensation in outdoor farming environments. The results suggest that sensitivity calibration is essential for real-time detection under outdoor conditions. The system demonstrates functional responsiveness suitable for low to moderate pest activity levels, ensuring timely pesticide activation and efficient pest management.

Table 3: Actual Sensitivity of the System.

Pest	**Sensitive Time**				
Grass hopper	**0.5m**	**1m**	**2m**	**3m**	**4m**
Trial 1	7.4s	10.6s	N/A	N/A	N/A
Trial 2	8.2s	N/A	N/A	N/A	N/A
Trial 3	6.6s	9.1s	14.3s	N/A	N/A
Cockroach					
Trial 1	4.8s	7.5s	16.6s	N/A	N/A
Trial 2	5.5s	9.4s	12.9s	N/A	N/A
Trial 3	5.1s	8.0s	18.3	20.2	N/A
Caterpillar					
Trial 1	8.2s	N/A	N/A	N/A	N/A
Trial 2	6.6s	9.1s	14.3s	N/A	N/A
Trial 3	5.5s	8.7s	14.7s	21.9s	N/A

Source: Authors, (2026).

III.3.3 Efficiency

Table 3 reveals that based on the maximum detection range of 4 m, the calculated sensor efficiency was 75% for caterpillars, 66.67% for cockroaches, and 29.17% for grasshoppers. Efficiency decreased for smaller insects and under higher environmental disturbance. This efficiency range is consistent with previous studies on infrared-based pest detection: one study found that IR-based sensor systems experienced notable drops in detectability for smaller arthropods under field conditions [20], while a comprehensive review reported that outdoor systems typically perform at lower efficiency than indoor setups due to wind, temperature and other disturbances [43]. The present results confirm that PIR sensors remain effective for larger pests under field conditions, validating their suitability for agricultural applications. The efficiency rates affirm the reliability of the detection mechanism for practical farming use, especially for medium and large pests. Further optimization through dual-sensor integration could improve accuracy for smaller pests, ensuring more comprehensive pest management.

Table 4 presents that the diaphragm pump delivered an average discharge rate of 12.7 L/min compared to its rated 13.3 L/min capacity, resulting in an efficiency of 95.49%. Minimal variation was observed during the trials, indicating consistent fluid transfer. The high pump efficiency aligns with literature showing that pump sets in agricultural systems can operate at high performance levels [47]. The small variance may be attributed to slight pressure drops in the tubing or minor voltage fluctuations. The consistency in performance ensures uniform pesticide application across all plant beds. The result validates the reliability and mechanical soundness of the pump mechanism. Its high performance supports sustained spraying activity, ensuring effective pest control coverage and reduced chemical waste, which are essential for organic pesticide application.

Table 4: Prevalent pest in the area.

Pest	Trial 1	Trial 2	Trial 3	Average
Discharge Rate	12.2 L/min	12.7 L/min	13.2 L/min	12.7 L/min

Source: Authors, (2026).

III.4 ECONOMIC FEASIBILITY

III.4.1 Payback Period

The labor cost for the plant taker was set at 100 pesos per hour. Based on the assumption that the automated pest control spraying system conserved two hours of the farmer's time every two days at the least, the payback period analysis indicated that the investment is projected to be recouped within eight months and five days. This supports the findings of [32] that payback period increases compared to the traditional method.

III.4.2 Internal Rate of Return

The IRR calculation was based on the assumption that the device would have a minimum expected useful life of one year. This metric assessed the percentage increase in the total investment cost of the automated pest control spraying system that will be returned over one year. The computed IRR was determined to be 39.6%, indicating that after a year of operation, an additional 39.6% of the total investment would be realized.

III.4.3 Benefit-Cost Ratio

The Benefit-Cost Ratio delineated the correlation between the benefits derived from the automated pest control spraying system and its overall cost. The computed ratio stands at 24:17, implying that for every ₱17.00 invested, there is an anticipated annual return of ₱24.00. This is aligned with the study of [23] & [32], which reported that automated system has higher benefit-cost ration compared to the traditional one. The financial indicators suggest that the automated pest control spraying system is economically feasible for smallholder farmers. Several studies have shown that automated agricultural systems with short payback periods—often under one year—are ideal for small-scale adoption [48-50].

The system significantly reduces labor costs, minimizes pesticide use, and enhances productivity, thereby contributing to financial sustainability. Similar efficiencies have been reported in smart agricultural systems that promote automation in pest management [32], [49], [50]. Economic analyses indicate that investing in an automated pest control spraying system can increase farmers' income and reduce operational expenses. Its affordability, efficiency, and ease of maintenance make it an accessible and practical solution for promoting sustainable agriculture in developing regions such as the Philippines.

IV. CONCLUSIONS

The automated system through the shielded Arduino Uno board efficiently interpreted signals from the sensor detected pests and managed the relay's switching function to operate the pump, ensuring the automated pest control spraying system 's alignment with its design. Key components, including a corrosion-resistant submersible pump, an accurate sensor, and chemical-resistant pipes, were carefully selected and validated for reliability in agricultural applications. Findings suggest an effective organic pest management as systems targets very highly encountered pest in the area such as the grasshopper, mantis and caterpillar. The sensor's effectiveness and sensitivity are directly proportional to the sample size and are influenced by environmental factors such as wind and ambient sound. The efficiency of the sensor computed was 75.00%, 66.67%, and 29.17% for caterpillar, mantis and grasshopper, respectively.

The reliability of system components was attained in this study, resulting a high efficiency for pump, achieving 95.49% and 93.46%, respectively, meeting the desired performance. The component durability which includes corrosion-resistant pump, accurate sensor, and chemical-resistant pipes. The automated pest control spraying system demonstrated economic viability with a payback period of 8 months and 5 days, and an internal rate of return exceeding the cost by 39.46%, yielding an annual return of 24 pesos for every 17 pesos invested. This shows significant economic and operational advantages. The short payback period and high IRR highlight its financial benefits, while the careful selection of reliable components and efficient system design ensure effective pest management and cost savings.

The system's ability to operate efficiently with a low labor cost and its resilience to environmental factors further enhance its practicality and value in agricultural applications. Findings of this study recommends the following recommendations to further enhance the system's performance and impact. To enhance sensor sensitivity and accuracy, an implementation of regular calibration schedule to maintain optimal sensor performance and accuracy, especially in varying environmental conditions. Consider incorporating more advanced sensor technologies, such as infrared or camera-based sensors, for a more accurate detection mechanism and reduce false detections. Conduct thorough field trials to determine the optimal placement of sensors for maximum effectiveness, taking into account factors like wind direction, plant height, and pest behavior.

To improve system reliability and durability, continue to establish a routine maintenance schedule, including cleaning, lubrication, and inspection of system components, to prevent malfunctions and extend the system's lifespan. To conduct further field trials and economic analysis, conduct large-scale field trials under diverse agricultural conditions to assess the system's performance and scalability in real-world scenarios. Conduct a detailed economic analysis, considering factors like labor costs, pesticide usage, crop yield, and market prices, to evaluate the long-term economic benefits of the system. By addressing these recommendations, the automated pest control spraying system can be further optimized to provide significant economic, environmental, and social benefits to farmers and the agricultural industry as a whole.

Future versions of the system may integrate locally available renewable energy sources to improve sustainability, as demonstrated by recent studies on unconventional energy harvesting methods such as alluvial soils [51], solar energy [52], [53], or even wind energy [53]. Overall, the system represents a sound investment with both economic and operational benefits. It has a multifaceted impact, offering significant economic, operational, environmental, and practical benefits. It represents a modern, efficient, and sustainable solution for pest management in agriculture, with strong potential for long-term advantages.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Bless Ampuan, Kenneth Saldo, Noel Angelo Espinar.
Methodology: Bless Ampuan, Kenneth Saldo, Noel Angelo Espinar.
Investigation: Bless Ampuan, Kenneth Saldo, Noel Angelo Espinar, Miguel Gonzalo Olmedo, Rey Mark Sumayop, Brix Ivan Cu and Arnol Galon.
Discussion of results: Bless Ampuan.
Writing – Original Draft: Bless Ampuan.
Writing – Review and Editing: Bless Ampuan.
Resources: Bless Ampuan, Kenneth Saldo, Noel Angelo Espinar, Miguel Gonzalo Olmedo, Rey Mark Sumayop, Brix Ivan Cu and Arnol Galon.
Supervision: Bless Ampuan.
Approval of the final text: Bless Ampuan, Kenneth Saldo, Noel Angelo Espinar, Miguel Gonzalo Olmedo, Rey Mark Sumayop, Brix Ivan Cu and Arnol Galon.

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