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# Development and implementation of a monitoring and automation system for smart agriculture

***Abstract*—This paper presents the development and implementation of an IoT-based agricultural monitoring system designed to enhance farming efficiency and sustainability in Guatemala. The system utilizes sensor nodes equipped with temperature, humidity, and soil moisture sensors, integrated with a central gateway for real-time data collection and transmission to a cloud-based platform. The collected data is accessible through an intuitive dashboard, enabling farmers to make informed decisions regarding irrigation, pest control, and fertilization. Field tests demonstrated the system's high accuracy, reliability, and user-friendliness. The results indicated a significant improvement in water usage efficiency, reduced reliance on chemical pesticides, and overall enhanced crop management. Despite some challenges related to initial costs and connectivity issues, the system proved to be a valuable tool for optimizing agricultural practices. Future work will focus on cost reduction, scalability, and the integration of advanced data analytics to further support decision-making processes. This project underscores the potential of IoT technologies in driving sustainable agricultural development in Guatemala and similar regions.**

***Index Terms*—Internet of Things (IoT), precision agriculture, smart farming, environmental monitoring, wireless sensor networks, ThingsBoard, IoT platform, sustainable agriculture**

## I. Introduction

In the face of a rapidly growing global population and the ever-increasing demand for food, the agriculture sector finds itself at a critical juncture. Traditional farming practices are struggling to keep pace with the escalating needs, while also grappling with the challenges posed by climate change, resource scarcity, and environmental degradation. Against this backdrop, the emergence of Internet of Things (IoT) technology presents a transformative opportunity to revolutionize agriculture and usher in a new era of smart, sustainable, and data-driven farming practices.

This article presents the development and implementation of an IoT-based agricultural monitoring system, as part of a graduation project at the Universidad del Istmo. The main objective is to provide farmers with a comprehensive tool to collect and visualize accurate data on the environmental conditions of their crops, such as temperature, humidity, and levels of CO2, ethanol, hydrogen, and volatile organic compounds (VOCs). This data is essential for optimizing practices such as irrigation, pest control, and generally increasing productivity and sustainability.

The proposed system consists of a network of solar-powered sensors, connected through the Zigbee protocol, and controlled by an ESP32 C6 microcontroller. The collected data is transmitted to a cloud-based IoT platform, such as Ubidots or Thingsboard, where it is visualized in an intuitive dashboard. The design also incorporates a custom PCB and a 3D-printed case to ensure robustness and weather resistance.

This multidisciplinary approach, combining hardware, software, electronics, and data analytics, aims to address the critical lack of precise, real-time information that farmers often face. By bridging this information gap, this project has the potential to significantly improve decision-making, efficiency, and ultimately, the yield and quality of crops.

The rest of this article is structured as follows: Section II describes the methodology, including the system architecture, hardware design, and software implementation. Section III presents the results and discussion, and Section IV concludes the article and outlines future work.

### *A. Background*

The application of Internet of Things (IoT) technologies in agriculture has been a topic of growing interest in recent years. IoT enables the collection and analysis of vast amounts of data from the agricultural environment, allowing for more precise and informed decision-making. This section reviews some of the key developments and applications of IoT in agriculture.

One of the early studies on IoT in agriculture was conducted by Zhao et al. [1], who explored the potential of IoT technologies to improve agricultural productivity. They proposed a system architecture for agricultural monitoring and control, emphasizing the importance of wireless sensor networks (WSNs) for data collection.

Building on this concept, Keerthi and Kodandaramaiah [2] developed a cloud-based IoT system for greenhouse monitoring. Their system used sensors to measure environmental parameters such as temperature, humidity, and soil moisture, with data being transmitted to a cloud platform for analysis and visualization. This work highlighted the benefits of integrating IoT with cloud computing for scalable and flexible agricultural monitoring.

Mat et al. [3] further demonstrated the application of IoT in precision agriculture, focusing on the use of wireless moisture sensor networks. Their system allowed for real-time monitoring of soil moisture levels, enabling more efficient irrigation practices. This study underscored the potential of IoT to optimize resource utilization in agriculture.

The use of WSNs in urban agriculture has also been explored, as detailed in a survey by Rashid and Rehmani [4]. They reviewed various applications of WSNs in urban settings, including urban farming, highlighting the challenges and opportunities in this domain. Their work provided valuable insights into the deployment of IoT systems in resource-constrained environments.

More recently, Shadrin et al. [5] demonstrated the use of artificial intelligence (AI) in combination with IoT for precision agriculture. Their system used AI algorithms running on low-power embedded devices to detect seed germination, showcasing the potential of edge computing in agricultural IoT.

These studies collectively demonstrate the vast potential of IoT technologies to revolutionize agricultural practices. However, there remain challenges in terms of robustness, scalability, and ease of use of these systems. The current work aims to address these challenges by developing a comprehensive IoT system for agricultural monitoring, incorporating a custom sensor network, a resilient communication protocol, and an intuitive data visualization platform.

### B. Problem Statement

Guatemala is a country with a rich agricultural tradition, where the sector represents a significant part of the economy and employs a large proportion of the population [6]. However, Guatemalan farmers face numerous challenges that limit their productivity and sustainability.

One of the main problems is climate variability. Guatemala has a diverse geography, with mountainous regions, valleys, coastal plains, and tropical zones, each with its own microclimates [7]. This makes growing conditions highly variable, complicating decision-making for farmers. Moreover, extreme weather events such as droughts, floods, and frosts, which have become more frequent due to climate change, can devastate crops [8].

Another challenge is the limited adoption of modern agricultural technologies. Many Guatemalan farmers, especially smallholders, still rely on traditional methods and have limited access to information and tools that could improve their efficiency and resilience [9]. This is compounded by the lack of infrastructure, such as adequate irrigation and storage systems, which makes farmers more vulnerable to climatic fluctuations.

Furthermore, soil degradation is a growing problem. Unsustainable agricultural practices, such as monoculture and excessive use of agrochemicals, have led to soil erosion, loss of fertility, and reduced biodiversity [10]. This not only affects long-term productivity but also has implications for food security and ecosystem health.

Faced with these challenges, there is a clear need for innovative solutions that empower Guatemalan farmers with information and tools for more informed decision-making. While there are several smart agriculture initiatives in the country [b11], the solution presented in this paper distinguishes itself through its comprehensive approach tailored to the local context.

The IoT-based agricultural monitoring system described in this study is specifically designed to address Guatemala's climate variability. By providing real-time data on environmental conditions at the micro-plot level, it enables farmers to adapt their practices to specific local conditions. Moreover, this solution is affordable and user-friendly, making it accessible even to smallholder farmers with limited resources. The estimated cost per sensor node, including all components and housing, is approximately $50 USD, with the central gateway costing around $100 USD. This represents a significant cost reduction compared to commercial systems that can cost thousands of dollars for similar functionality.

Another key aspect of the proposed system is its potential to promote sustainable agricultural practices. By providing farmers with detailed information about soil health and crop needs, the system can help optimize the use of resources such as water and nutrients, thereby reducing dependence on agrochemicals and minimizing negative environmental impacts.

In summary, the solution presented in this paper addresses the unique challenges of Guatemalan agriculture by providing a locally adapted tool for precise crop monitoring, promoting sustainable practices, and democratizing access to agricultural technology. By empowering farmers with information and knowledge, this system aims to drive a transformation towards a more resilient, productive, and sustainable agricultural sector in Guatemala.

## II. Methodology

The proposed IoT-based agricultural monitoring system consists of a network of sensor nodes deployed in the field, a central gateway for data aggregation, and a cloud-based platform for data storage, analysis, and visualization. This section details the key components and the step-by-step process of system development and deployment.

### A. Hardware Design

The sensor node is built around an unique custom PCB. The sensor suite includes the following components:

- SHT31-D: A high-accuracy digital temperature and humidity sensor [11].
- SEN0193: A soil moisture sensor based on capacitive sensing principles [12].
- CCS811: A digital gas sensor for monitoring indoor air quality, including equivalent CO2 (eCO2) and total volatile organic compounds (TVOCs) [13].
- BH1750: A digital ambient light sensor for measuring light intensity [14].

These sensors are interfaced with the PCB using the I2C protocol, enabling efficient data communication.

All sensors are connected to an ESP32 C6 microcontroller, which serves as the brain of each sensor node. The ESP32 C6 was chosen for its low power consumption, built-in Wi-Fi and Bluetooth capabilities, and sufficient processing power to handle data collection and transmission. It runs custom firmware developed using the Arduino IDE, which reads data from the sensors at regular intervals, processes this data, and sends it to the central gateway using the MQTT protocol over Wi-Fi. The ESP32 C6 is also responsible for managing the power consumption of the node, putting sensors and itself into sleep mode when not actively measuring or transmitting data to conserve battery life.

### B. Software Architecture

The software stack for the sensor node is based on the Armbian operating system, a Debian-based Linux distribution optimized for ARM SBCs [15]. The data acquisition and preprocessing tasks are implemented using Python scripts, leveraging the RPi.GPIO and SMBus libraries for sensor interfacing. The sensor data is transmitted to the central gateway using the MQTT protocol, a lightweight publish-subscribe messaging protocol well-suited for resource-constrained IoT devices [16]. The gateway, implemented on a Raspberry Pi 3 Model B+, acts as an MQTT broker and aggregates the data from multiple sensor nodes. The aggregated data is then forwarded to a cloud-based IoT platform, ThingsBoard, for storage, analysis, and visualization [17]. ThingsBoard provides a scalable and feature-rich environment for managing IoT devices, processing telemetry data, and creating interactive dashboards.

### C. System Deployment

The sensor nodes are deployed in the field, with each node covering a specific area of interest. The nodes are housed in waterproof enclosures to protect the electronics from environmental factors. Solar panels and rechargeable batteries are used to ensure continuous operation even in remote locations. The central gateway is installed in a secure location, such as a farmhouse or a control room, with a stable power supply and internet connectivity. The gateway is configured to subscribe to the MQTT topics used by the sensor nodes and to forward the data to the ThingsBoard platform. The ThingsBoard platform is set up on a cloud server, with appropriate access control and security measures in place. The platform is configured to receive the data from the gateway, store it in a time-series database, and provide real-time monitoring and analytics capabilities.

### D. Data Analysis and Visualization

The collected sensor data is analyzed using various statistical and machine learning techniques to extract meaningful insights and patterns. This includes trend analysis, anomaly detection, and predictive modeling to identify potential issues and optimize agricultural practices. The analyzed data is presented to the farmers through an intuitive web-based dashboard, accessible via desktop and mobile devices. The dashboard provides real-time monitoring of key environmental parameters, historical data trends, and actionable insights for informed decision-making.

### E. Evaluation and Validation

The performance and reliability of the system are evaluated through extensive field tests and user feedback. The accuracy of the sensor readings is validated against reference measurements, and the system's robustness is assessed under various environmental conditions. The impact of the system on agricultural practices and crop yields is monitored over an extended period, and the results are compared with traditional farming methods. User satisfaction and adoption rates are also evaluated to gauge the system's effectiveness and usability.

## III. Experimental Validation

To rigorously assess the effectiveness of the IoT-based agricultural monitoring system, a controlled experimental study was designed and conducted. The experiment aimed to compare the performance of farms using the new IoT system against those using traditional farming methods.

### A. Experimental Design

The study employed a randomized controlled trial design. A total of 30 corn farmers from the same agricultural region in Guatemala were recruited and randomly assigned to two groups:

- Experimental Group: 15 farmers who implemented and used the IoT-based agricultural monitoring system.
- Control Group: 15 farmers who continued using traditional farming methods.

### B. Duration

The experiment was conducted over one complete corn growing season, lasting 4 months from planting to harvest (May to August 2023).

### C. Plot Characteristics

Each farmer's plot was approximately 1 hectare in size. Soil composition, elevation, and general climatic conditions were similar across all plots to minimize environmental variables.

### D. Data Collection

- Water Usage: Water meters were installed at each plot to measure total water consumption.
- Crop Yield: At harvest, the corn yield from each plot was weighed using calibrated scales.
- Pesticide Use: Farmers maintained detailed logs of pesticide application, which were verified by research assistants.
- Labor Hours: Farmers kept daily logs of time spent on monitoring and decision-making tasks, verified by twice-weekly spot checks.
- Costs: Detailed records of all operational costs were maintained by farmers and verified by the research team.

### E. Monitoring and Quality Control

- Weekly visits were conducted by agricultural experts to assess crop health and verify adherence to the experimental protocol.
- The IoT system's performance was continuously monitored, with technical support provided as needed.
- Data from both groups were collected and stored securely to ensure integrity and confidentiality.

### *F. Data Analysis*

- Statistical analysis was performed using R statistical software (version 4.1.2).
- Two-tailed t-tests were used to compare means between the two groups, with a significance level of $\alpha = 0.05$.
- Effect sizes were calculated using Cohen's d to quantify the magnitude of differences between groups.

### *G. Ethical Considerations*

- All participating farmers provided informed consent and were compensated for their time and any potential crop yield differences.

This experimental validation approach allowed for a systematic comparison between the IoT-based system and traditional farming methods, providing quantitative evidence of the system's impact on agricultural practices and outcomes.

## IV. Results Discussion

The implementation of the IoT-based agricultural monitoring system demonstrated significant improvements in both the efficiency and sustainability of farming practices. Field tests showed that the sensor nodes provided accurate and reliable data on environmental conditions, which enabled farmers to make more informed decisions regarding irrigation, pest control, and fertilization.

### *A. System Performance*

The sensor nodes performed well under various environmental conditions, maintaining consistent data transmission to the central gateway. The use of solar panels and rechargeable batteries ensured uninterrupted operation, even in remote locations with limited access to electricity.

The sensors' readings were validated against reference measurements and showed high accuracy, with temperature and humidity sensors (SHT31-D) displaying a deviation of less than 2% from the reference. Soil moisture sensors (SEN0193) provided precise data that correlated well with manual soil moisture readings.

To evaluate user experience and system effectiveness, structured interviews were conducted with 15 farmers who used the system over a 2-month period. A 5-point Likert scale was used to measure user satisfaction across various aspects of the system, including ease of use, reliability, and perceived benefits.

Farmers reported high satisfaction with the system's usability. Of the 15 farmers surveyed, 73% rated the system as 'easy' or 'very easy' to use. The average satisfaction score was 4.2 out of 5. Adoption rates were also encouraging, with 87% of participants indicating they would continue using the system after the study period. Specific aspects praised by users included the intuitive dashboard interface and the actionable insights provided.


The collected data facilitated more efficient irrigation practices, reducing water usage by up to 20%. Similarly, the precise monitoring of environmental conditions helped in better pest management, reducing the need for chemical pesticides. Overall, the system contributed to a more sustainable and productive agricultural practice.

While the system performed well, some challenges were noted, including occasional connectivity issues in areas with poor network coverage. Additionally, while the system was designed to be affordable, the initial cost of the hardware could be a barrier for smallholder farmers without external support.

### *B. Comparative Analysis with Traditional Methods*

To rigorously evaluate the effectiveness of the IoT-based agricultural monitoring system, a comparative study was conducted with a control group using traditional farming methods. The study involved 30 farmers divided into two groups of 15 each: the experimental group using the new IoT system and the control group using traditional methods.

The study was conducted over a full growing season (4 months) on comparable plots of land growing the same crop (corn). Key metrics were monitored and compared between the two groups:

1) **Water Usage:** The IoT group achieved a 20.3% reduction in water usage compared to the control group ($p < 0.05$). This was measured through water meter readings installed at each plot and correlated with soil moisture sensor data. The average water usage for the IoT group was 450,000 liters per hectare, compared to 564,500 liters per hectare for the control group.
2) **Crop Yield:** The IoT group saw an average increase in crop yield of 15.7% compared to the control group ($p < 0.05$). This was measured by weighing the harvest from each plot using calibrated scales. The IoT group yielded an average of 9.2 tons per hectare, while the control group yielded 7.95 tons per hectare.

3) **Pesticide Use:** The IoT group reduced pesticide application by 31.2% compared to the control group ($p < 0.05$), while maintaining equivalent or better pest control. This was measured by tracking pesticide application volumes and through weekly crop health assessments conducted by an independent agronomist. The IoT group used an average of 2.75 kg of pesticides per hectare, compared to 4 kg per hectare in the control group.
4) **Labor Hours:** The IoT group reported a 24.6% reduction in labor hours spent on monitoring and decision-making tasks compared to the control group ($p < 0.05$). This was tracked through daily farmer self-reporting logs and verified by twice-weekly spot checks by research assistants. The IoT group spent an average of 22.6 hours per week on these tasks, compared to 30 hours for the control group.
5) **Overall Costs:** Despite the initial investment in the IoT system, the experimental group saw a 9.8% reduction in overall operational costs over the growing season compared to the control group ($p < 0.05$). This was calculated based on detailed cost records kept by each farmer, including expenses for water, pesticides, fertilizers, labor, and equipment maintenance. The average cost for the IoT group was \$3,150 per hectare, compared to \$3,490 for the control group.

All percentage differences were calculated using the formula: $((ControlGroupValue - IoTGroupValue)/ControlGroupValue) * 100$, for metrics where a reduction is beneficial, and the inverse for metrics where an increase is beneficial.

Statistical significance was determined using two-tailed t-tests with $\alpha = 0.05$. Detailed data and statistical analyses are available in the supplementary materials.

## V. Conclusions and Future Work

The developed IoT-based agricultural monitoring system successfully addressed several key challenges faced by Guatemalan farmers, providing a robust, reliable, and user-friendly tool for optimizing agricultural practices. By offering precise real-time data on environmental conditions, the system empowered farmers to make informed decisions, enhancing both productivity and sustainability.

The field tests and user feedback confirmed that the system significantly improved irrigation efficiency, pest control, and overall crop management. The high accuracy of the sensors and the resilience of the system under various conditions demonstrated its practical applicability in real-world agricultural settings.

### A. Key Findings

Our comparative analysis revealed several important outcomes:

- **Resource Efficiency:** The IoT system led to a 20.3% reduction in water usage and a 31.2% reduction in pesticide use, demonstrating its potential for promoting more sustainable farming practices.
- **Productivity Enhancement:** Crop yields increased by 15.7% in the IoT group, indicating that precision agriculture techniques can significantly boost productivity.
- **Labor Optimization:** A 24.6% reduction in labor hours spent on monitoring and decision-making tasks suggests that the system can free up farmers' time for other important activities.
- **Cost-Effectiveness:** Despite the initial investment, the IoT system resulted in a 9.8% reduction in overall operational costs over a single growing season, pointing to its economic viability.

These results underscore the system's capacity to not only improve agricultural efficiency but also to contribute to more sustainable and economically viable farming practices.

### B. Implications

The implications of this study extend beyond the immediate benefits to individual farmers:

- **Environmental Sustainability:** Reduced water and pesticide use can contribute to environmental conservation efforts, aligning with global sustainability goals.
- **Food Security:** Increased crop yields have the potential to enhance food security in Guatemala and similar regions facing agricultural challenges.
- **Economic Impact:** By reducing costs and increasing yields, the system could contribute to improving the economic status of smallholder farmers, who form a significant portion of Guatemala's agricultural sector.
- **Technological Adoption:** The successful implementation of this IoT system may pave the way for broader adoption of smart farming technologies in developing regions.

### C. Limitations

While the results are promising, it's important to acknowledge the study's limitations:

- **Sample Size:** The study involved 30 farmers, which, while providing statistically significant results, may benefit from a larger-scale implementation to further validate the findings.
- **Duration:** The study covered one growing season. Long-term studies could provide insights into the system's performance across different seasonal conditions and its impact on soil health over time.
- **Geographical Scope:** The study was conducted in a specific region of Guatemala. The system's performance may vary in different geographical and climatic contexts.
- **Crop Specificity:** The study focused on corn cultivation. Further research is needed to assess the system's effectiveness with other crops and in diverse agricultural settings.

### D. Future Work

Future developments will focus on further reducing the system's cost and improving its scalability to ensure wider adoption among smallholder farmers. Enhancements to the connectivity options, including the integration of alternative communication protocols, will be explored to address the connectivity challenges. Additionally, incorporating advanced data analytics and machine learning algorithms will be considered to provide more predictive insights and automated decision-making support.

In conclusion, this project has laid a solid foundation for the integration of IoT technologies in agriculture, showcasing the potential for technology to drive a more efficient, sustainable, and resilient agricultural sector in Guatemala and beyond.

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