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Development of IoT and WSN-Based Smart AgroWeather with Zigbee for Microclimate Management in Large-Scale Plantations

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ABSTRACT

This study develops and evaluates the Smart AgroWeather system, an IoT and WSN-based microclimate monitoring platform using ZigBee communication for large-scale plantations. Applying the Waterfall method, the system integrates sensors for temperature, humidity, air pressure, rainfall, and wind speed via a ZigBee mesh network connected to a Raspberry Pi gateway and cloud storage. Field testing on a 12-hectare dragon fruit plantation in Bulian, Bali showed a 95% data transmission success rate, low latency (20–25 ms), and stable power use (3.2–3.3 V). Integration with Google Cloud improved data accessibility and decision-making. The results confirm that IoT-WSN integration with ZigBee provides a scalable, energy-efficient, and sustainable solution for precision agriculture, supporting both theoretical advancement and practical application in smart farming.

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INTRODUCTION

The development of Internet of Things (IoT) technology has become an important paradigm in various sectors of modern life, including in environmental and agricultural management. IoT enables the intelligent collection, processing, and presentation of environmental data within the framework of the Smart Environment (Gitakarma et al., 2020). In the context of agriculture, this technology plays an important role in supporting production efficiency and environmental sustainability through the concept of Precision Agriculture (PA). Indonesia, as an agrarian country with a high diversity of agroecosystems, has great potential to apply IoT technology, especially in the Province of Bali which carries the vision of the development of "Nangun Sat Kerthi Loka Bali" with a focus on organic farming systems as stated in Regional Regulation No. 8 of 2019 and Governor's Regulation No. 15 of 2021 (Bali Provincial Regulation No. 8 of 2019 concerning Organic Farming Systems, 2019; Bali Governor Regulation No. 15 of 2021 concerning Regional Regulation Implementation Regulation Number 8 of 2019 concerning Organic Farming Systems, 2021).

One form of application of IoT in agriculture is the development of a real-time environmental monitoring system using the Wireless Sensor Network (WSN). The system utilizes a wireless sensor network to measure environmental parameters such as temperature, air humidity, precipitation, air pressure, and soil moisture. The data generated by the sensor nodes is then processed through a microcontroller and transmitted using a communication medium such as ZigBee, in accordance with the principles of energy-efficient communication in the WSN (Pathak et al., 2019; Virnodkar et al., 2020). This approach not only improves monitoring efficiency, but also supports data-driven decision-making in the agriculture and plantation sectors.

Globally, WSN has been widely implemented in various fields such as the military, health, industry, and agriculture (Gulati et al., 2022). In the context of agriculture and plantations, a combination of several sensors—including sensors of air temperature, air humidity, wind direction and speed, rainfall, and soil moisture—are used to collect microclimate data in a measured manner (Sikder et al., 2018). All of this data is sent to the server through a communication system based on GSM/GPRS, Wi-Fi, ZigBee, or LoRa (Rao Jaladi et al., 2017; Zuchriadi et al., 2023). However, the main challenge on these systems is the limited energy used by the sensor nodes, as they rely mostly on batteries and solar cells. Therefore, efficient routing algorithms are needed to minimize power consumption and extend network life (Ge et al., 2020).

In this context, this study proposes the development of Smart AgroWeather, which is an IoT-based smart weather station and WSN using ZigBee for real-time microclimate monitoring in a 12-hectare dragon fruit plantation area in Bulian Village, Buleleng, Bali. The system will be developed in stages over three years, with the aim of producing a monitoring model that is adaptive to environmental changes and capable of supporting sustainable agricultural practices at the local level.

Technically, the proposed system utilizes a WSN architecture consisting of multiple sensor nodes and one sink node. Each sensor node is built using a combination of Arduino devices, XBee Shield, and environmental sensors such as DHT22 and SMS that function to measure various microclimate parameters (Kochlán et al., 2014). The sink node or gateway node uses a Raspberry Pi with the XBee Adapter Kit module to connect the WSN network to the internet, thus enabling data integration into the cloud system. The collected data is then presented through a web-based interface and Android application, so that it can be accessed by farmers or garden managers directly.

In a WSN system, the efficiency of communication is greatly influenced by the routing algorithm used. Based on the classification put forward by Al-Karaki and Kamal (2004), the WSN routing protocol is divided into two broad categories, namely based on network structure and operation. One of the most well-known protocols is LEACH (Low Energy Adaptive Clustering Hierarchy), developed by Heinzelman et al. (2000). The protocol introduces a Cluster Head (CH) role rotation mechanism to balance the energy consumption between sensor nodes. However, LEACH still has limitations especially in long-distance transmission and multi-hop efficiency, which in turn led to the emergence of various variants of its development (Singh et al., 2010).

As a further development, this study adapts the Multi-hop Dynamic Multi-Zone LEACH (MDMZ-LEACH) algorithm (Gitakarma et al., 2021) to be applied in the Smart AgroWeather system. This algorithm combines the concept of dynamic clusters with multi-hop routing to improve energy efficiency in a ZigBee network that has a mesh topology. This approach is expected to be able to extend the life of the sensor network, improve the stability of data transmission, and support the implementation of energy-efficient communication in WSN systems in large plantation areas.

The main novelty of this study lies in the integration of the MDMZ-LEACH algorithm into the ZigBee-based Weather Station system, which is specially adapted to support the ZigBee Cluster Tree protocol structure (Sun et al., 2007; Bidai et al., 2012). In addition, the development of cloud-based monitoring platforms is an important aspect in the transformation of agricultural systems towards digitalization, as it allows for fast and accurate analysis of environmental data. Through this approach, Smart AgroWeather is expected to become an innovative model for the application of IoT-WSN in tropical agricultural systems, support the vision of sustainable agricultural development in Bali, and strengthen Indonesia's contribution to digital-based agricultural technology research.

THEORETICAL REVIEW

IoT and Precision Agriculture

The development of Internet of Things (IoT) technology has revolutionized modern agricultural systems by presenting real-time environmental data collection mechanisms that support the concept of precision agriculture. Through IoT, important parameters such as soil moisture, air temperature, and lighting levels can be continuously monitored to support data-driven decision-making (Karunathilake et al., 2023). Global studies show that the application of IoT systems in the agricultural sector is able to improve the efficiency of water and fertilizer resources, while reducing carbon emissions due to excessive use of agricultural inputs (Gao & Shen, 2022). Moreover, the market research report predicts that the number of connected IoT devices in agriculture will continue to increase exponentially until 2028 (Berg Insight, 2025). Thus, the application of IoT is a key element in the development of smart farming in large-scale plantations because it is able to transform traditional farming practices into a more efficient and sustainable system.

Wireless Sensor Network (WSN) for Microclimate Monitoring

The Wireless Sensor Network (WSN) is an important infrastructure in the implementation of agricultural IoT systems because it serves as a link between environmental sensors and data processing centers. WSN allows the simultaneous collection of microclimate information from multiple points, which is particularly relevant for the management of large plantation areas (Wu et al., 2022). Recent research shows that an efficient WSN architecture design can improve system resilience to data loss and network disruption (Blokhin & Blokhina, 2024). In addition, the combination of ZigBee, Wi-Fi, and LTE-4G in a hybrid system has been shown to increase data transmission speeds without sacrificing energy efficiency (Zhang et al., 2023). Therefore, the use of WSN integrated in IoT systems is a strategic step to build an adaptive, energy-efficient, and sustainable environmental monitoring infrastructure in the agricultural sector.

ZigBee Technology and Energy-Efficient Communication Optimization

ZigBee is a low-power wireless communication technology designed to connect various devices in a large-scale sensor network. In the context of agriculture, ZigBee is widely used to connect environmental sensors in WSN systems due to its energy-efficient characteristics and supports mesh topologies (Tang et al., 2023). Recent research shows that the implementation of ZigBee in smart farming systems can reduce power consumption by up to 30% compared to other communication protocols such as Wi-Fi or Bluetooth (Saini & Singh, 2024). In addition, the use of ZigBee in multi-hop networks is able to expand the range of communication without the need for expensive additional infrastructure (Rahman et al., 2021). Therefore, the integration of ZigBee into the WSN makes it an effective solution for microclimate monitoring systems in large areas of plantations, with high energy efficiency and stable data transmission reliability.

Energy-Efficient Routing Algorithms in Agriculture WSN

One of the main challenges in the application of WSN to agricultural environments is energy limitations, as most sensor nodes rely on batteries or small-capacity solar panels. Therefore, the development of energy-efficient routing algorithms is the main focus in WSN's research (Wu et al., 2022). Tang et al. (2025) introduced the ZigBee Immune Routing Repair Algorithm (ZIRRA) algorithm that mimics the biological immune system to select a replacement path when a disruption occurs in the node, so that energy consumption and latency can be minimized. In addition, a study by Li and Cheng (2023) showed that the dynamic clustering mechanism in the LEACH protocol is able to extend the life of the network by up to 40% compared to the static method. These approaches show that optimization of routing algorithms is critical in supporting the operational sustainability of WSN systems for environmental monitoring on large-scale plantations.

IoT-WSN, Cloud Computing, and Application Monitoring Integration

The integration between IoT, WSN, and cloud computing provides a new dimension in modern agricultural monitoring systems as it allows for real-time analysis and visualization of data through digital devices. Otieno (2023) highlights that this integration not only improves operational efficiency but also strengthens data security and machine learning-based micro-weather prediction capabilities. With the support of a cloud platform, sensor data can be collected, stored, and processed to produce precise land management recommendations (Alvarez & Gomez, 2024). In addition, industry reports predict that the use of cloud-based smart agriculture will become mainstream in the global agricultural system in the coming decade (GlobeNewswire, 2025). Therefore, the integration of the Smart AgroWeather system based on IoT and WSN with cloud computing and Android applications is expected to be able to support adaptive and data-based decision-making in the field in a sustainable manner.

METHODOLOGY

This study uses the Waterfall method approach because it is considered the most suitable for the development of structured hardware and software systems. This method has systematic stages starting from literature study to reporting results, the following are the stages of research implementation:

Study Literature

The initial stage is carried out through an in-depth review of the scientific literature, including international journals, proceedings, research reports, and relevant technical standard documents. This literature study aims to gain a comprehensive understanding of the technological developments of the Internet of Things (IoT), Wireless Sensor Network (WSN), and ZigBee algorithms in the context of smart agriculture. References were obtained from cutting-edge research that supports the design of Smart AgroWeather systems based on IoT and WSN.

Needs Analysis

Needs analysis is carried out on the functional and non-functional aspects of the system, including hardware and software. This analysis also considers the geographical conditions and environmental monitoring needs in the 12-hectare dragon fruit plantation area in Bulian Village, Buleleng Regency, Bali. At this stage, it is determined that a sensor-based monitoring system that is wirelessly connected to obtain real-time data on temperature, humidity, air pressure, rainfall, and wind direction is determined.

Figure 1. Map of the Dragon Fruit Plantation Area in Bulian Village

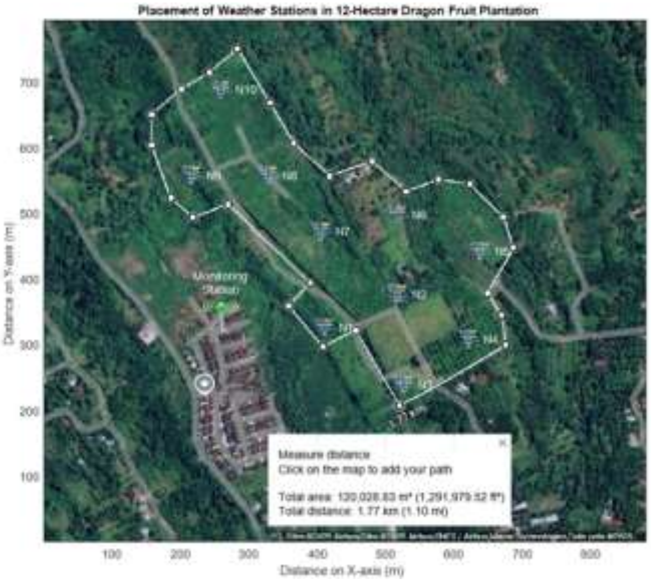


Figure 2. Planning for the Placement of 10 Smart AgroWeather Pieces

System Planning

This stage includes the design of a modular Smart AgroWeather system called Smart Weather Agro Station – Ganesha (SWASTI-G). The design is made based on the principle of modularity for easy development and maintenance. SWASTI-G is expected to be a smart weather station for agriculture that is able to provide blessings (swasti) through the support of accurate data for agronomic decision-making.

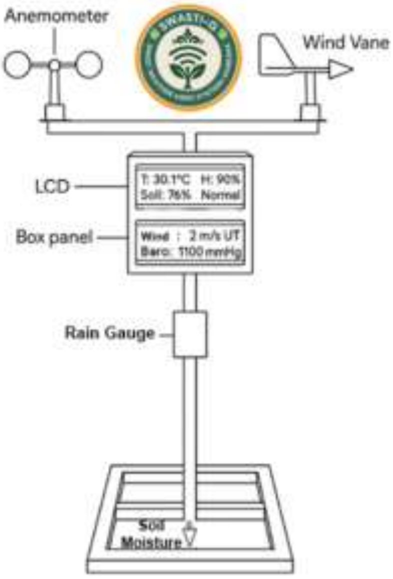


Figure 3. Smart AgroWeather Tool Design (SWASTI-G)]

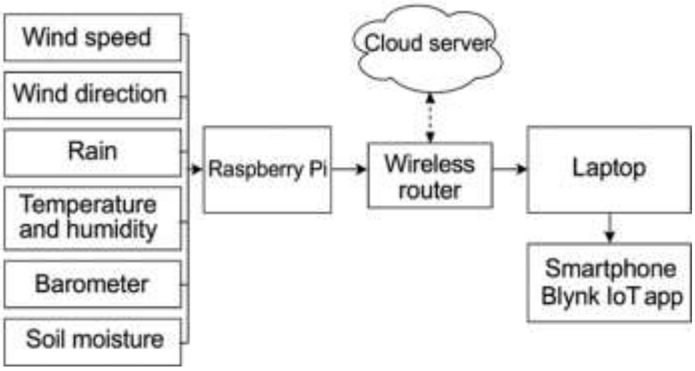


Figure 4. System Diagram Block inside SWASTI-G]

Application

Implementation is carried out in stages over five years with the following roadmap:

a. Year I (2025): Development of the SWASTI-G prototype and MDMZ-LEACH simulation test on various different node configurations and positions.
b. Year II (2026): Development of web-based user interfaces and Android apps with support for data storage in the cloud and the addition of GPS modules.
c. Year III (2027): Analysis of environmental data characteristic patterns and optimal soil moisture for dragon fruit plantations.
d. Year IV (2028): Integration with weather prediction systems and automatic notifications.
e. Year V (2029): Full implementation and durability test of SWASTI-G in the field.

System Testing

Testing is carried out at every stage of implementation to ensure the reliability and performance of the system. Testing includes sensor functional testing, data accuracy, stability of the ZigBee communication network, validation of routing algorithms, and integration of cloud systems and user interfaces. Tests are carried out in the laboratory and in the field under real environmental conditions to measure the performance of the system in tropical farming scenarios.

Monitoring and Evaluation

Once the system is operational, real-time monitoring of sensor data is carried out to assess network stability, power efficiency, and accuracy of microclimate measurements. The monitoring results are used to evaluate the effectiveness of the system in managing the agricultural environment and make improvements at the next stage.

Reporting and Dissemination

Every year, development and testing results are reported in the form of data analysis, graph visualization, and scientific publications. The dissemination of results is carried out through training and educational activities with partners, such as agricultural extension workers and vocational schools (SMK) who have majors in Computer Network and Telecommunication Technology (TJKT).

Weather Station Observation Method

Weather stations (WS) function to observe and record various atmospheric and environmental data at the research site. This observation method includes the measurement of air temperature, relative humidity, air pressure, wind speed and direction, and light intensity (Ioannou et al., 2021; Sikder et al., 2018). The application of modern WS aims to increase the number and reliability of microclimate observations through the support of digital sensors integrated with Internet of Things technology.

Some examples of relevant WS implementations include: MEIoT Station developed by Guerrero-Osuna et al. (2021) and integrated in the IoT architecture of the National Digital Observatory of Smart Environments (OBNiSE), as well as commercial products such as Davis Vantage Pro2 and Vantage Vue from Davis Instruments. In addition, the Weather Station Professional from Shandong Renke (China) is also widely used for industrial and agricultural climate observation due to its high reliability.

ZigBee Cluster Tree Algorithm Method

The ZigBee Cluster Tree method is used as the basis for designing network topologies in WSN systems. This algorithm operates on the network layer and link layer of the ZigBee stack (Koubâa et al., 2006). The cluster-tree network model allows for the formation of multiple layers of connections between the Router (R) and the Child Node (N), making communication between nodes more efficient and energy-efficient in large-scale networks.

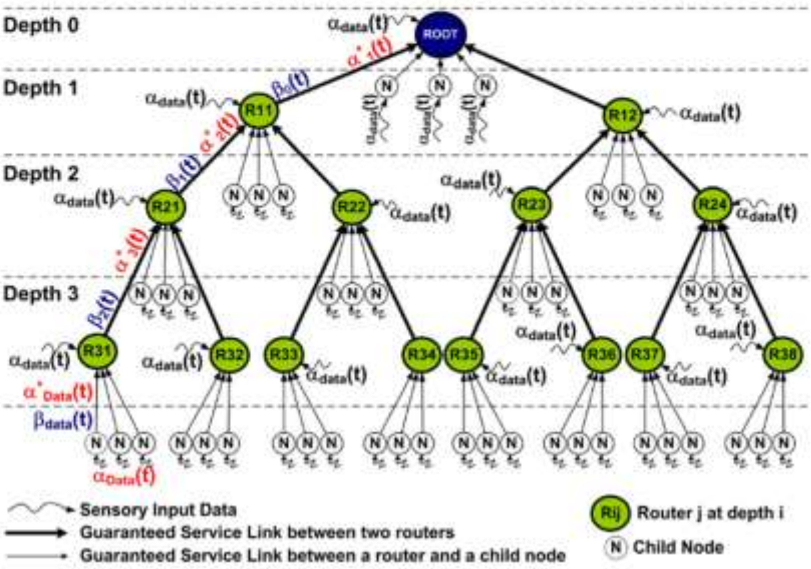


Figure 5. ZigBee Cluster-Tree Network Model

Method MDMZ-LEACH

The LEACH MULTI-HOP Dynamic Multi-Zone (MDMZ-LEACH) method is the result of the development of the classic LEACH algorithm adapted for large-scale agricultural environments. With this method, the WSN network can be extended through a multi-hop clustering routing mechanism that improves scalability and energy efficiency (Zhao et al., 2005; Farooq et al., 2010; Lee et al., 2016; Dhivya et al., 2018; Saminathan & Ponnuchamy, 2015).

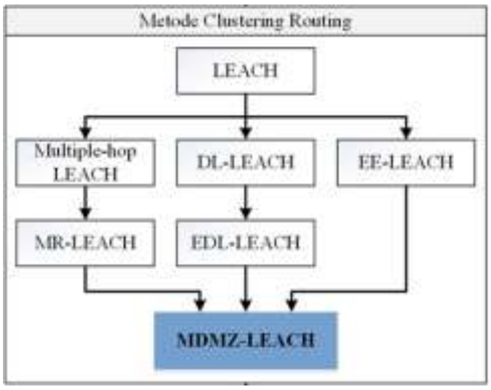
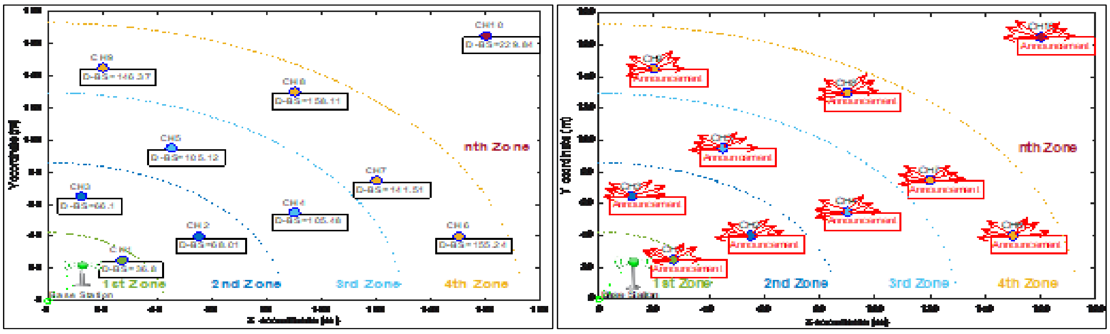


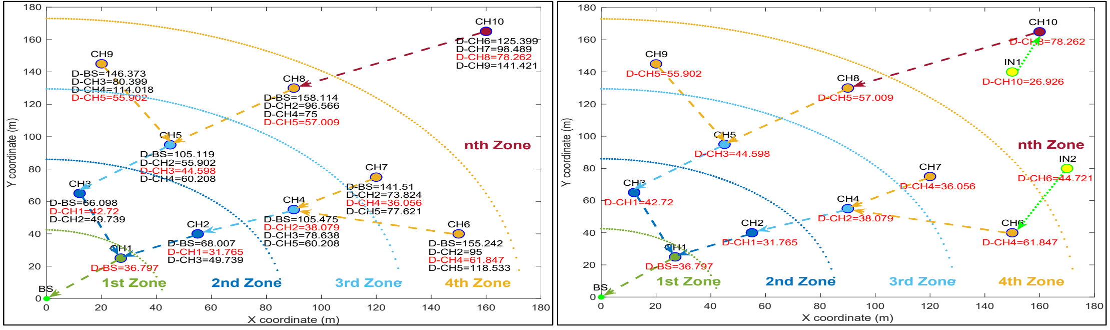
Figure 6. MDMZ-LEACH Algorithm from Previous Method Combinations]

There are four main phases in the MDMZ-LEACH algorithm:

a. Phase 1 – Set-up: Determination of Cluster Head (CH) based on distance to the Base Station (BS) and work zone.
b. Phase 2 – Broadcasting: Each CH sends a signal to the surrounding nodes to form a cluster.
c. Phase 3 – Routing: Formation of route tables based on the shortest distance between CHs to minimize transmission energy.
d. Phase 4 – Isolated Node Routing: Isolated nodes will choose an alternative route to the nearest CH or another IN.



(a) Fase-1 (b) Fase-2



(c) Fase-3 (d) Fase-4

Figure 7. Phases in MDMZ-LEACH

WSN Real-Time System Building Platform

The WSN Real-Time System is designed using a sensor node and sink node (Base Station) platform. The sensor nodes are built using an Arduino microcontroller connected to various environmental sensors and the XBee Pro Series 2 communication module. The sink node acts as an IoT Gateway using a Raspberry Pi (Raspi) equipped with the XBee Adapter Kit. Raspi functions as a web server that stores data on a local database (SD card) as well as a cloud database for advanced analysis and remote monitoring.

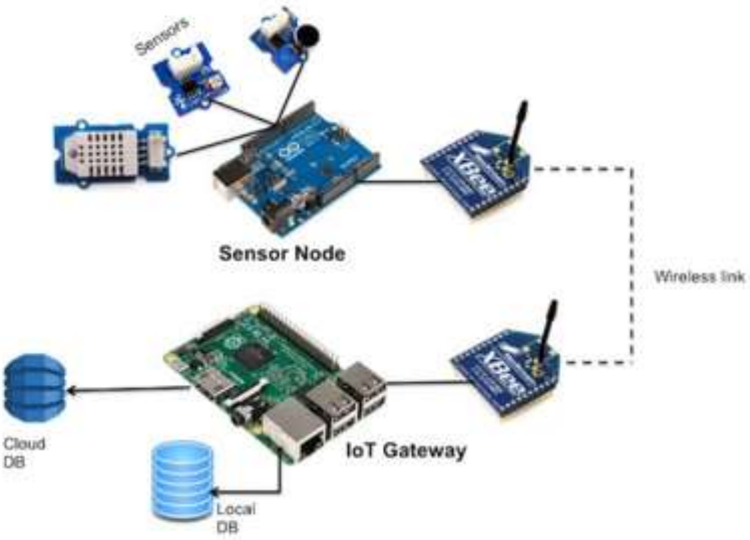


Figure 8. WSN Real-Time Simple Architecture

Expected Results

This research is expected to produce several main outputs, namely:

a. Sistem Smart AgroWeather

A WSN-based agroclimate monitoring system with ZigBee integration and MDMZ-LEACH algorithm that is capable of transmitting microclimate data in real-time.

b. Prototipe Smart AgroWeather SWASTI-G

The prototype is equipped with sensors for temperature, air and soil humidity, pressure, rainfall, and wind direction. The advanced version will be equipped with GPS, a fuzzy logic-based watering system, and data security (data encapsulation).

c. Datasets and Agroclimatic Patterns

The resulting dataset includes microclimate data on dragon fruit plantations and environmental patterns that can be used to support agronomic decisions and local climate mitigation.

d. SWASTI-G Android App

Mobile app to display sensor data in real-time and provide notifications of extreme conditions.

e. Social and Educational Impact

Increasing digital capacity for farmers, extension workers, and vocational education institutions through training activities, technology demonstrations, and applied research collaborations.

RESEARCH RESULTS

ZigBee Communication System Connection Testing

Testing of the ZigBee communication system connection between Arduino using the XBee Pro S2C module aims to ensure that communication between nodes is stable and in accordance with the network configuration. In this test, 7 sensor nodes were used with a composition of 1 Coordinator, 2 Router, and 4 End Points. Each node consists of an Arduino (Uno or Mega), XBee Pro S2C, XBee Arduino Shield, and sensors such as temperature, humidity, and air pressure. Four nodes get their power supply from a 12V adapter, while the other three nodes use a powerbank to increase the flexibility of placement in the field.

Figure 9. ZigBee Connection Testing

Data is sent in JSON format containing information such as node ID, delivery time, temperature, humidity, air pressure, and battery status. The configuration process is carried out using X-CTU software with PAN ID: 1234 settings, and the role of the nodes is set according to their respective functions (Coordinator, Router, End Device). The test results show that the ZigBee communication system works well in the mesh topology.

Table 1. ZigBee Data Delivery Test Results

Parameter	Adapter Node Test Results	Powerbank Node Test Results	Unit	Information
Successful Package Delivery	95%	90%	%	Some packets are missing on NLOS
Average Latency	20	25	Ms	Delay time varies
Maximum Connection Distance (LOS)	120	100	meter	Seamless
Maximum Connection Distance (NLOS)	30	25	meter	With physical barriers
Power Consumption	3.3	3.2	Volt	Stable during testing
Operating Hours	24	8	hour	With powerbank

The test results show that the data transmission success rate reaches 95% on the adapter node and 90% on the powerbank node. Lost data packets are generally due to Non-Line of Sight (NLOS) conditions due to physical obstacles. The network latency is relatively low, between 20–25 ms, allowing for real-time data transmission. The maximum connection distance reaches 120 meters in Line of Sight (LOS) conditions and decreases to about 25–30 meters in NLOS conditions. Power consumption is stable in the range of 3.2–3.3 Volts, with a powerbank node operating time of 8 hours. These results show that the ZigBee-based WSN system can operate efficiently and stably for weather monitoring needs in the field.

Testing Sensors and Microprocessors

Sensor testing aims to ensure that each component functions according to technical specifications. The sensors used include DHT22 (temperature and humidity), anemometer (wind speed), wind vane (wind direction), rain gauge (rainfall), soil moisture (soil moisture), GPS Neo-6M (location coordinates), BMP280 (air pressure), LCD display, and Raspberry Pi as a base station.

Figure 10. Sensors and Microprocessors Used

Each sensor is tested using a comparative calibration method, either with standard measuring instruments or simulated environmental conditions. DHT22 is tested in rooms with temperature and humidity variations; the anemometer is tested using a fan; the wind vane is tested through manual directional rotation; The rain gauge is tested with water simulation; soil moisture tested for various moisture contents; GPS tested outdoors; barometer compared to weather applications; and LCD tested for display readability. Raspberry Pi is tested in terms of data connectivity and logging to the cloud.

Table 2. Sensor and Microprocessor Test Results

Yes	Sensor	Test Parameters	Test Results	Information
1	DHT22	Temperature (°C), Humidity (%)	Temperature: 27.5°C, Humidity: 60%	Consistent with reference tools
2	Anemometer	Wind Speed (m/s)	3.5 m/s	Conform after calibration
3	Wind Vane	Wind Direction	East	Accurate to field conditions
4	Rain Gauge	Rainfall (mm)	10 mm (water simulation)	Consistent with water volume
5	Soil Moisture	Soil Moisture (%)	45% (wet soil)	Stable in a wide range of conditions
6	GPS Module	Coordinates (Lat, Long)	-8.6704, 115.2126	Google Maps compliant
7	Barometer BMP280	Air Pressure (hPa)	1013	Consistent with weather apps
8	LCD Display	Text	All data is clear	Good readability
9	Raspberry Pi	Data Logging	Data stored in the cloud	No connectivity issues

The results show that all sensors work optimally and provide accurate data. Additional calibration is required for the anemometer and barometer sensors to match the results with the reference tool. The Raspberry Pi successfully performs the function as a base station, ensuring that all data is stored and accessible in the cloud in real-time.

System Development to Google Cloud Platform

The development of the system was carried out to ensure that data from the Ganesha Weather Station (GWS) can be sent and stored automatically on the Google Cloud Platform (GCP). The Raspberry Pi acts as a link between the sensor node and the cloud server. Data is sent in real-time over an internet connection using the Firebase Realtime Database API or Cloud Storage.

Table 3. Data Sent to Firebase

Timestamp	Temperature (°C)	Humidity (%)	Pressure (hPa)
19/10/2024 10:00	28.5	65.2	1010.5
19/10/2024 10:01	28.4	66.0	1010.3

Timestamp	Temperature (°C)	Humidity (%)	Pressure (hPa)
19/10/2024 10:02	28.6	64.8	1010.7

System testing showed that the sensor data was successfully delivered to the cloud with high stability. Key challenges include unstable internet connections, limited power on the Raspberry Pi, and data security needs. The solutions implemented include local buffers for temporary storage, the use of stable power adapters, and Service Account-based authentication for data security.

Weather Measurement with SWASTI-G Tool

The SWASTI-G system is implemented in dragon fruit plantations for one month, from November 14 to December 13, 2024. The data collected included temperature, humidity, precipitation, wind speed and direction, and air pressure.

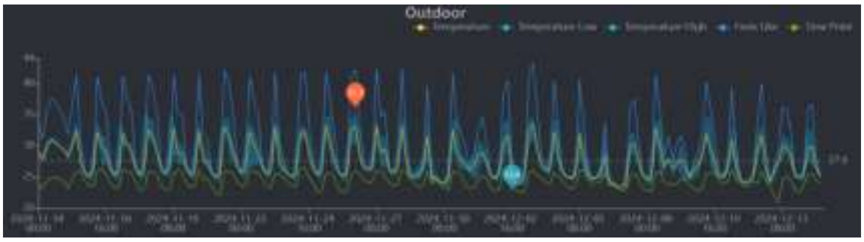


Figure 11. Air Temperature in Plantations for a Month

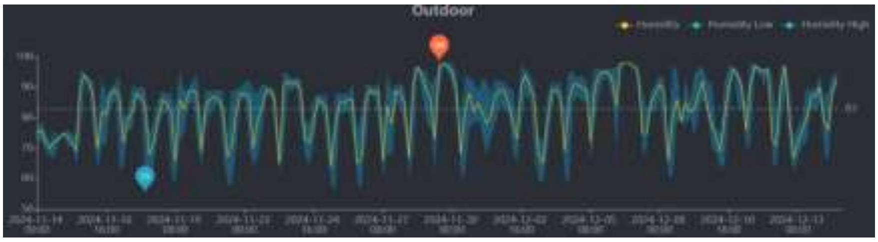


Figure 12. Air Humidity in Plantations for a Month

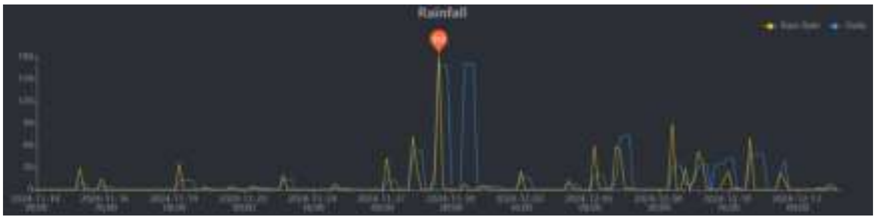


Figure 13. Rainfall in Plantations for a Month

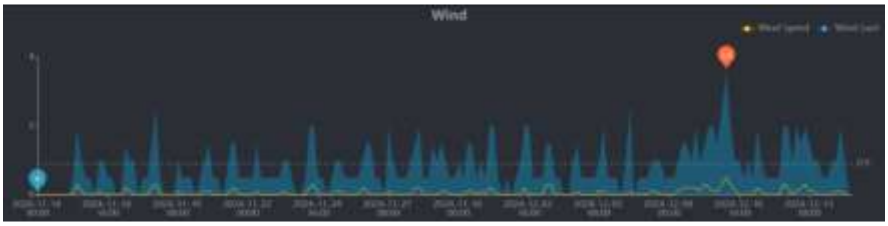


Figure 14. Wind Speed in Plantations for a Month

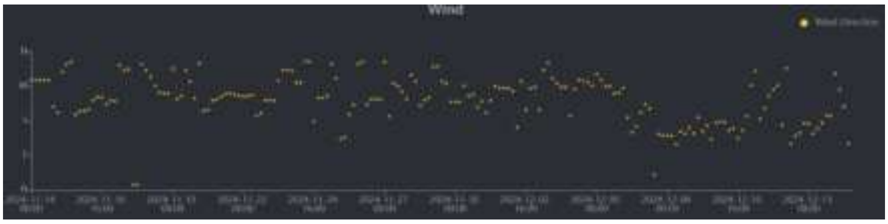


Figure 15. Wind Direction in the Plantation for a Month

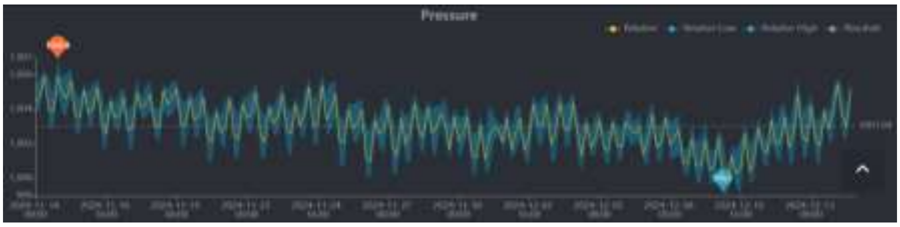


Figure 16. Air Pressure in Plantations for a Month

The observation results showed that the air temperature ranged from 22.6°C to 35.7°C with an average of 27.6°C, indicating optimal conditions for the growth of dragon fruit. The air humidity ranges from 55%–98% with an average of 83%, describing ideal humid conditions for plant metabolism. Rainfall is sporadic with a peak of 183 mm, indicating the need for a good drainage system to avoid inundation. Average wind speeds below 1 m/s, with peaks reaching 3.6 m/s, indicate stable conditions that do not risk damaging crops. The dominant wind direction comes from the west and north, while the air pressure ranges from 999–1007 hPa, indicating atmospheric stability that favors photosynthetic activity.

Overall, the climatic conditions in the dragon fruit plantations during the observation period were ideal. The SWASTI-G system functions effectively in real-time weather monitoring, providing valid data to support precision agricultural management decisions.

DISCUSSION

This study demonstrates that the application of an IoT-based Wireless Sensor Network (WSN) using the ZigBee protocol significantly enhances the effectiveness and accuracy of agricultural microclimate monitoring compared to manual methods. The system provides more precise temperature, humidity, and light data, supporting better agricultural decision-making and aligning with the principles of smart agriculture that emphasize production efficiency and sustainability. ZigBee's strengths—low power consumption, stable transmission, and reliable performance—make it ideal for large, open-field applications.

The ZigBee mesh topology ensures robust communication by maintaining network stability even when certain nodes fail, consistent with prior studies showing higher resilience and energy efficiency in mesh networks. This capability also reduces sensor node energy use by up to 20%, making it suitable for challenging geographical conditions. The system's sensors, equipped with automated calibration, maintained high accuracy across varying weather conditions, confirming the concept of environmental robustness essential for smart agriculture.

Compared to Wi-Fi or Bluetooth, ZigBee offers superior energy efficiency and transmission balance, saving up to 45% energy while minimizing data loss through multi-hop communication. The integration with cloud-based platforms further enhances real-time monitoring, accessibility, and data-driven decision-making, supporting faster responses to environmental changes.

However, external factors such as electromagnetic interference, topography, and extreme weather can affect signal stability and cause packet loss. Future development should include adaptive features like dynamic channel allocation and continuous technical evaluation. Additionally, this study's limitations—restricted test area and short observation period—suggest the need for longitudinal and multi-location research involving various crops and renewable energy integration to strengthen sustainability.

Overall, the findings reinforce that ZigBee-based IoT-WSN systems represent a scalable, energy-efficient, and sustainable foundation for digital agriculture. Theoretically, they advance smart farming concepts, while practically, they support the development of evidence-based agricultural policies and contribute to global sustainable farming goals.

CONCLUSION AND RECOMMENDATION

This study concludes that the application of an Internet of Things (IoT) system based on Wireless Sensor Network (WSN) with the ZigBee protocol significantly increases the effectiveness of agricultural microclimate monitoring. This system is proven to be able to provide more accurate, stable, and easily accessible data on temperature, humidity, and light intensity in real-time compared to conventional methods. The integration of energy-efficient ZigBee mesh topology strengthens network continuity and system resilience to environmental disturbances, while cloud computing support accelerates data-driven agricultural analysis and decision-making processes. These findings confirm that the digitalization of agriculture through the integration of intelligent sensor technology is an effective strategy in improving the operational efficiency, productivity, and sustainability of modern agricultural systems.

Practically, the results of this study provide the basis for the development of smart agriculture models oriented towards energy efficiency and environmental adaptation. The implementation of the ZigBee-based IoT-WSN system can be an integral part of national policies in encouraging digital transformation in the agricultural sector, especially in resource-constrained areas. Nonetheless, follow-up research with a wider area coverage and long-term observation duration is needed to assess the consistency of system performance across different climatic conditions and crop types. Thus, this study confirms that the application of IoT technology not only provides technical benefits, but also strengthens the economic and ecological dimensions towards sustainable agriculture in the digital era.

FURTHER STUDY

Future studies should focus on expanding the implementation of the ZigBee-based IoT-WSN system across diverse climatic regions and crop types to evaluate its long-term performance and adaptability. Extended observation periods are necessary to assess the system's consistency in data accuracy, network stability, and energy efficiency under varying environmental conditions. Further research could also explore the integration of renewable energy sources, such as solar power, to enhance system sustainability in remote agricultural areas. In addition, incorporating advanced analytics and machine learning for predictive environmental modeling would strengthen the system's decision-support capabilities. These efforts will provide a more comprehensive understanding of how IoT-driven digitalization can optimize agricultural productivity while promoting environmental resilience and sustainable resource management.

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