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Article

IoT for Agricultural Innovation: Enhancing Robusta Coffee Seedling Growth in Controlled Environments with Intelligent Air Quality Control System (IAQCS)

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Abstract: Advancements in Internet of Things (IoT) technology have revolutionized agriculture by enabling real-time monitoring and automated environmental control to optimize crop growth. This study focuses on evaluating the impact of IoT implementation on greenhouse environmental stability and the growth of Robusta Coffee Clone BP 308 seedlings, emphasizing plant height and leaf count as key parameters. The IoT system incorporates DHT11/DHT22 sensors for temperature and humidity monitoring, soil pH sensors, and an ESP8266 WiFi module for data transmission to an IoT platform. Additionally, Fuzzy Logic algorithms were employed to analyze the data and regulate environmental conditions such as temperature and humidity automatically. The experimental design compared IoT-based systems with conventional methods in a controlled greenhouse environment. Results demonstrated that the IoT system significantly enhanced environmental stability, maintaining an average temperature of 26.59°C and humidity of 86.46%, compared to conventional systems with greater fluctuations of 28.43°C and 82.69%. This stability positively impacted seedling growth, with IoT-treated plants achieving significantly higher heights and leaf counts at weeks 3, 6, and 9. By week 9, IoT-treated seedlings averaged a height of 24.00 cm with 11.73 leaves, outperforming non-IoT seedlings, which reached only 14.07 cm with 8.27 leaves. These findings highlight IoT's potential to create optimal growth conditions, reduce environmental stress, and enhance photosynthetic efficiency. Furthermore, IoT's precision in managing resources supports sustainable agriculture, making it an essential tool for improving productivity and competitiveness, especially in coffee cultivation, a key commodity in Indonesia.

Keywords: Coffee Robusta; IoT; IAQCS; Nursery

1. Introduction

Advances in information and communication technology, particularly the application of the Internet of Things (IoT), have brought about a revolution in the agricultural sector, including in coffee cultivation. IoT enables real-time environmental data collection and algorithm-based automatic control, which is crucial for creating optimal conditions for plant growth. In the context of coffee farming, especially in the early phase of seedling growth, the stability of environmental parameters such as temperature, humidity, and soil pH is key to success. Research shows that uncontrolled fluctuations in temperature and humidity can inhibit plant physiological processes, reduce photosynthesis, and slow growth, especially in sensitive crops such as coffee [1]. In addition, the application of precision technologies in agriculture can also improve production efficiency and sustainability, as expressed by [2], who highlighted the importance of training programs to accelerate the adoption of precision agriculture technologies among agricultural professionals.

Robusta coffee, the leading variety in Indonesia, faces major challenges due to extreme climate change that causes temperature and humidity instability, potentially reducing photosynthetic efficiency and yield [3]. The optimal temperature for coffee is 20-28°C with 70-90% humidity [4], and deviations from these conditions can negatively affect crop quality. To overcome this, the research integrates IoT technology with Fuzzy Logic algorithms to create an automatic control system in the greenhouse. The system uses sensors to monitor soil temperature, humidity, and pH, with data sent to an IoT platform for analysis and decision-making. IoT has been shown to improve environmental stability by up to 90%, compared to conventional methods that are vulnerable to weather changes [5], thus supporting agricultural efficiency and sustainability by optimizing resources and adapting to climate change [6].

The novelty of this study is the integration of IoT technology in coffee nurseries in mini greenhouses using the automation of the intelligent air quality control system (IAQCS) which has not been previously applied and only on horticultural plants. The results of this research can be controlled through the web and application to be subsequently given to coffee farmers how to use it on their smartphone devices.

This research aims to evaluate the impact of IoT implementation on greenhouse environmental stability and its effect on the growth of Robusta Coffee Clone BP 308 seedlings, especially on the parameters of plant height and number of leaves. The method used in this research is a comparison between IoT-based and non-IoT (conventional) systems to determine the extent to which IoT technology can create stable and optimal environmental conditions for plant growth. The results of this research are expected to provide practical and data-driven solutions to support efficiency in modern agricultural systems. In addition, the application of IoT in agriculture is also relevant in supporting agricultural sustainability by increasing the productivity and competitiveness of coffee farming, which is one of the leading commodities in Indonesia.

2. Materials and Methods

2.1 Material

The tools used in this research include DHT11/DHT22 sensor, soil pH sensor, ESP8266 WiFi module, automatic sprayer system with relay and solenoid valve modules, and power adapter. IoT platform, fuzzy logic algorithm, web and mobile applications are used for remote monitoring and control. Jumper cables, breadboards, LED indicators, resistors, capacitors, and protective boxes are also included. Robusta Coffee Clone BP 308 seedlings as research objects in a greenhouse to simulate controlled growth conditions.

2.2 Method

2.2.1 Planning Stage

The design of the innovative system is planned, which involves collecting environmental data around the plant seedlings, such as temperature, humidity, and soil pH. These data are measured using the DHT11/22 sensor for temperature and humidity, and a soil sensor for soil pH. The collected data is then transmitted via an ESP8266 WiFi-supported microcontroller to an IoT server for processing using the AI Fuzzy Logic method.

Applications of Fuzzy Logic in AI: Control Systems: Fuzzy logic is widely used in control systems where precise mathematical models of the system are difficult to develop. It is used in applications like automatic transmission systems. Fuzzy Logic in a Temperature Control System, Imagine a room temperature control system where the objective is to maintain a comfortable temperature. Fuzzy Sets: The temperature can be classified into fuzzy sets like "cold," "warm," and "hot." Each set has a membership function (e.g., a bell-shaped curve) that defines how much the current temperature belongs to each set. Rules: The system might have rules like: If the temperature is cold, then set the heater to high, If the temperature is warm, then set the heater to medium, If the temperature is hot, then set the heater to low. Inference: Based on the current temperature, the system evaluates the rules and calculates a fuzzy output (e.g., how much heat is needed). Defuzzification: The system then calculates the precise heater setting (e.g., 75% power) based on the fuzzy output.

This system controls an automatic sprayer that maintains the temperature and humidity within optimal values. The designed system also enables real-time monitoring and control via web and mobile applications, which can be accessed and operated remotely by the user. shown in figure 1.

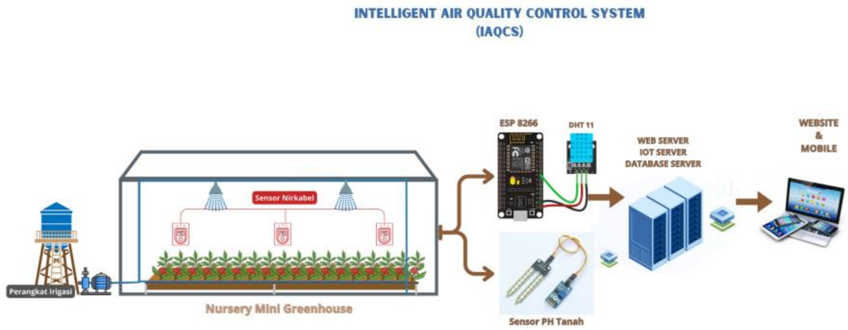

Figure 1. Intelegent Air Quality Control System (IAQCS)

2.2.2 Design Stage

During the design phase, an automatic control system based on IoT and AI is designed to regulate the temperature and humidity in the green house. The system design includes hardware components such as the IoT circuitry, temperature and humidity controllers, and web and mobile applications for remote operation and monitoring. This system design is discussed through Focus Group Discussions (FGD) involving experts and stakeholders to ensure that the system meets the needs of the nursery. This stage also includes the design of the PCB and the IAQCS system, which will be installed in the green house. shown in figure 2.

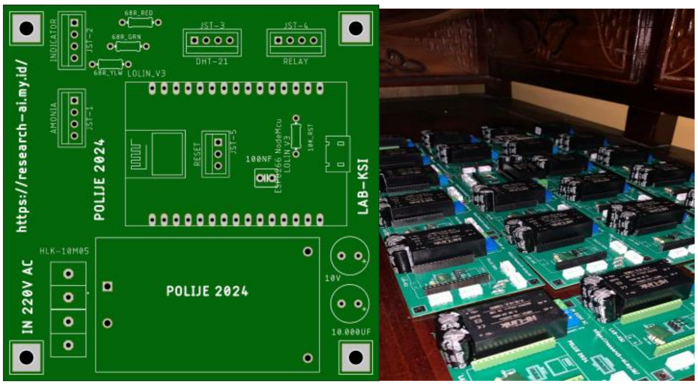

Figure 2. PCB design and grounded circuitry of the IAQCS System

2.2.3 Implementation Stage

The hardware and software developed in the design stage are installed and implemented. The automatic control system is set up to regulate the temperature and humidity in the green house, and the IoT and AI devices are programmed to perform automatic monitoring and control functions. This stage is carried out in September, with the success indicator being the proper installation and operational functionality of the IoT and AI-based automatic control system for regulating the temperature and humidity in the green house.

2.2.4 Observations on Coffee Seedling Growth

In this study, the growth of coffee seedlings was observed under two conditions: with the use of IoT-based environmental control and without IoT (non-IoT). The observations focused on key growth parameters, including plant height and leaf number, across different growth stages (week 3, week 6, and week 9).

2.2.5 Data Analysis

In this study, the data analysis method is designed to compare the effects of IoT and non-IoT technologies on the growth of coffee seedlings. The analysis begins with Levene's test to check for the equality of variances between the IoT and non-IoT groups. Paired t-tests are then conducted to examine the differences in mean plant height and leaf count at weeks 3, 6, and 9. Additionally, temperature and humidity measurements from both methods are compared to assess environmental stability, using standard deviation as a measure of consistency. All collected data is analyzed using statistical software, and p-values and confidence intervals are calculated to determine whether the differences between the two groups are statistically significant, with a p-value < 0.05 indicating a significant difference.

3. Results and Discussion

The use of Internet of Things (IoT) technology in measuring the temperature and humidity of the environment has been proven to have a significant impact on the stability and consistency of the conditions of the coffee plant growing area as needed. Based on the research, the temperature of the growing area using the IoT method shows an average of 26.59°C with a standard deviation of 0.73, while the non-IoT (conventional) method shows an average temperature of 28.43°C with a standard deviation of 3.49. This data shows that the IoT method is able to maintain a more stable ambient temperature, which is essential for optimal plant growth conditions [7][8]. In contrast, non-IoT methods show greater temperature fluctuations, reflecting instability caused by external factors such as weather conditions in the area [9] [10] (Figure 3.).

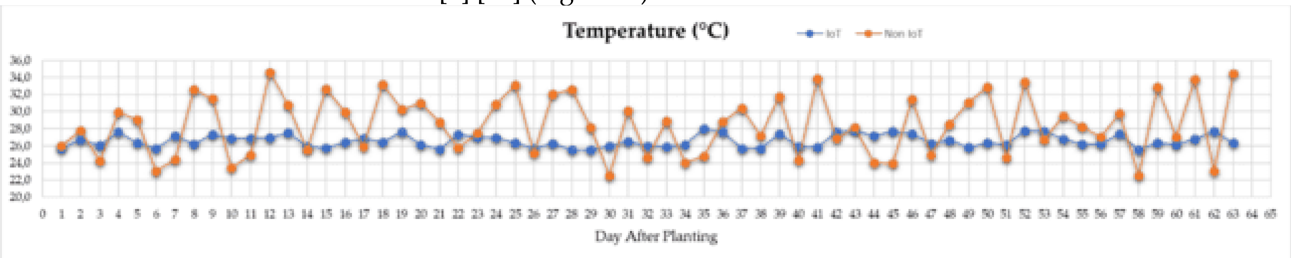

Figure 3. Air Temperature Fluctuation between IoT and non-IoT Usage

Analysis of the ambient humidity showed a similar pattern. The average humidity measured using the IoT method was 86.46% with a standard deviation of 0.97, showing very stable and consistent results (Figure 4.). In contrast, the non-IoT method had an average humidity of 82.69% with a standard deviation of 11.55, reflecting high humidity fluctuations [11][12]. The instability of humidity in this conventional method indicates that environmental conditions are strongly influenced by external factors that are difficult to control, which can ultimately hinder plant growth [13][10].

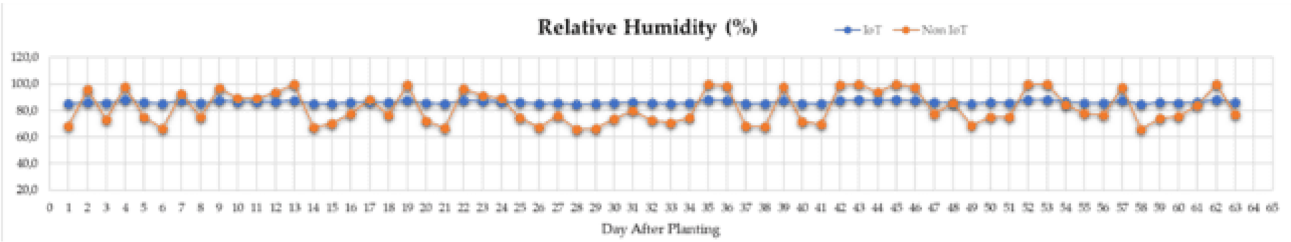

Figure 4. Air Humidity Fluctuation between IoT and No IoT Usage

The use of Internet of Things (IoT) technology in monitoring environmental conditions shows significant results on the stability and consistency of plant growth, as supported by statistical analysis of Levene's Test and t-test for Equality of Means. Based on temperature and humidity measurements, IoT provides better environmental control, which contributes to more optimal plant growth compared to non-IoT methods.

Table 1. Independent Samples Test (Levene's Test for Equality of Variances)

			Levene's Test for Equality of Variances		t-test for Equality of Means						
			F	Sig	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of The Difference Lower	Upper
Week 3	Plant Height	Non IoT	3.289	.080	-1.646	28	.111	-1.30000	.79002	-2.9183	.31828
		IoT			-1.646	21.85	.114	-1.30000	.79002	-2.9391	.33909
	Number of Leaf	Non IoT	.021	.885	-2.987	28	.006	-.80000	.26785	-1.3487	-.25132
		IoT			-2.987	27.98	.006	-.80000	.26785	-1.3487	-.25131
Week 6	Plant Height	Non IoT	.535	.471	-3.88	28	<,001	-3.7333	.96280	-5.71	-1.76113
		IoT			-3.88	27.83	<,001	-3.7333	.96280	-5.71	-1.76058
	Number of Leaf	Non IoT	7.729	.010	-3.652	28	,001	-2.93333	.80317	-4.5786	-1.2881
		IoT			-3.652	18.12	,002	-2.93333	.80317	-4.6199	-1.2468
Week 9	Plant Height	Non IoT	1.23	.277	-11.42	28	<,001	-9.93333	.86996	-11.715	-8.1513
		IoT			-11.42	26.98	<,001	-9.93333	.86996	-11.718	-8.1483
	Number of Leaf	Non IoT	1.149	.293	-4.627	28	<,001	-3.46667	.74918	-5.0013	-1.9320
		IoT			-4.627	25.11	<,001	-3.46667	.74918	-5.0093	-1.9240

Source: Prosesed data, 2024

Table 1 about Levene's Test results showed significant differences in variance in several plant growth parameters between groups without IoT and with IoT. At week 3, plant height showed a p value of 0.080, indicating no significant difference in variance between groups. However, the number of leaves showed a significant difference (p=0.006) with a value of t=-2.987, indicating that plants with IoT treatment had a higher average number of leaves than those without IoT. At week 6, the analysis of plant height showed a significant difference with a value of t=-3.88 (p<0.001), with a better average plant height in the IoT group and an average difference of -3.7333 cm (95% CI: -5.71 to -1.76113). The number of leaves also showed significant results (t=-3.652, p=0.001), where the IoT treatment produced more leaves than without IoT with a mean difference of -2.93333 leaves (95% CI: -4.5786 to -1.2881). At week 9, the t-test results showed that the IoT treatment had a very significant impact on plant height (t=-11.42, p<0.001) with a mean difference in height of -9.93333 cm (CI 95%: -11.715 to -8.1513). The number of leaves also followed the same pattern, with a t=-4.627 (p<0.001) and a mean difference of -3.46667 leaves (95% CI: -5.0013 to -1.9320).

The use of Internet of Things (IoT) technology in monitoring environmental conditions has a significant impact on environmental stability and growth of coffee seedlings, as shown through the analysis of temperature, humidity, and the results of the t-test on plant height and number of leaves (Table 2.). At week 3, although the difference in plant height between the IoT (10.38 cm) and non-IoT (9.91 cm) groups was not significant, the number of leaves in the IoT group (4.33 leaves) was more than the non-IoT (3.53 leaves, p=0.006). In the 6th and 9th week, the difference became more striking, with the height of IoT plants reaching 16.47 cm and 24.00 cm, much higher than non-IoT which was only 12.73 cm and 14.07 cm, and the number of IoT leaves was more (10.47 and 11.73 leaves) than non-IoT (7.53 and 8.27 leaves), with significant differences in both weeks (p<0.001). This is related to the ability of IoT to maintain a stable temperature (26.59°C) and consistent humidity (86.46%), which are essential for the growth of coffee seedlings, support the efficiency of plant physiological processes, and reduce environmental stress. In contrast, fluctuations in temperature (28.43°C) and humidity (82.69%) in the non-IoT method inhibited growth, indicating that IoT creates optimal conditions for healthier and more consistent plant growth.

Table 2. Comparison of Mean Plant Height and Number of Leaves

Treatment	Average Plant Height at…. Week (cm)			Average Number of Leaf at… Week (sheet)		
	3	6	9	3	6	9
Non IoT	9,91	12,73**	14,07**	3,53	7,53*	8,27**
IoT	10,38	16,47**	24,00**	4,33	10,47*	11,73**

*Notes: *) significantly different by paired t-test at 5% level; **) significantly different by paired t-test at 1% level.*

Source: Prosesed data, 2024

The significant improvement in Internet of Things (IoT)-treated crops can be explained by the ability of this technology to monitor and regulate plant environmental conditions more efficiently and accurately. IoT technology utilizes various sensors to collect real-time data on environmental factors that affect plant growth, such as soil moisture and air temperature. With this data, IoT systems can provide alerts or make automatic adjustments to ensure that the soil remains in optimal conditions, so that plants do not suffer from water shortages or excesses. Research shows that water shortage can cause stress in plants, which negatively affects their growth, while excess water can disrupt root respiration and cause root rot, which certainly hinders the growth of coffee seedlings [14].

Temperature sensors also play an important role in creating an optimal environment for plants. Temperatures that are too high or low can disrupt the photosynthesis process, ultimately affecting plant growth [15][16]. Temperature sensors connected to an IoT system can monitor air and soil temperatures constantly, and regulate the environment to keep the temperature at an ideal level for coffee plant growth. With more accurate and up-to-date data collected by the IoT system, farmers can make more informed and quicker decisions in managing their crops. For example, if a moisture sensor indicates that the soil is starting to lack water, the IoT system can instantly activate an automatic irrigation system to water the plants, or notify the farmer to perform manual watering[17].

Coffee plants are very sensitive to changes in environmental conditions, especially in their early growth stages. Extreme changes, such as temperatures that are too hot or too cold, or unbalanced soil moisture content, can cause coffee plants to stress, slow down their growth, or even cause permanent damage to the plants (Kumar & Jayaraman, 2020). With IoT technology, all these environmental factors can be monitored and controlled more accurately, creating more stable and optimal conditions for the plants. This is very helpful in improving the quality [18] and quantity of agricultural yields, as coffee plants grown under optimal conditions will develop faster, healthier, and have better resistance to diseases and pests[19].

Overall, the use of IoT technology in agriculture not only increases efficiency in the management of the crop environment, but also ensures faster and healthier growth for coffee plants. The accuracy of data obtained through sensors and real-time monitoring allows farmers to make more informed and strategic decisions in caring for their crops, which will ultimately contribute to more optimized yields. IoT technology opens up opportunities for coffee farming to develop in a smarter, more efficient, and more sustainable way [20]. Thus, the use of IoT technology in monitoring environmental conditions in crop growing areas provides better control and high stability, ensuring that environmental conditions remain in line with crop growing requirements. This is crucial to support healthy and optimal plant growth. On the other hand, without the use of IoT, environmental conditions become more volatile and dependent on the current situation, which can hinder plant growth and cause uncertainty in agricultural yields [21][22]. IoT technology offers a more reliable and efficient solution to maintain optimal environmental conditions for plant growth, ensuring that temperature and humidity remain within appropriate limits in real-time [23].

4. Conclusions

Based on the research conducted, it can be concluded that the use of Internet of Things (IoT) technology in monitoring environmental temperature and humidity has a positive impact on the stability of coffee plant growth conditions. IoT can maintain more stable temperature and humidity, 26.59°C and 86.46%, respectively, which support optimal growth, resulting in significant differences in plant height and number of leaves compared to the non-IoT method. Growing area conditions without the use of IoT showed greater fluctuations in temperature and humidity, which inhibited plant growth. This research shows that IoT not only improves the efficiency of environmental management, but also supports healthier and optimal plant growth, contributing to better and more sustainable agricultural yields.

Author Contributions:

Conceptualization, E Rosdiana, F Y Ali; E R Purwatiningsih, D R Hartadi and R Purbningtyas; methodology, E Rosdiana, F Y Ali; E R Purwatiningsih, D R Hartadi and R Purbningtyas; validation, E Rosdiana, F Y Ali; E R Purwatiningsih, D R Hartadi and R Purbningtyas; formal analysis, E Rosdiana, F Y Ali and D R Hartadi; investigation, E Rosdiana, F Y Ali; E R Purwatiningsih, D R Hartadi; and R Purbningtyas; resources, E Rosdiana, F Y Ali; E R Purwatiningsih, D R Hartadi and Purbningtyas; data curation, E Rosdiana, F Y Ali and D R Hartad; writing—original draft preparation, E Rosdiana and F Y Al; writing—review and editing, E Rosdiana and F Y Ali.

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