

Implementation of IoT-Based Weather Prediction System Using Machine Learning for Irrigation Optimization in Peatland Oil Palm Plantations

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ABSTRACT

Oil palm plantations on tropical peatlands require adaptive irrigation management due to unstable environmental conditions. This study proposes an IoT-based environmental monitoring and rainfall prediction system for irrigation optimization in oil palm plantations located in Palembang, South Sumatra, Indonesia. The proposed system integrates multiple environmental sensors with an ESP32 microcontroller for real-time monitoring and wireless data transmission. Historical environmental data were processed using the Long Short-Term Memory (LSTM) algorithm for short-term rainfall prediction under multiple forecasting scenarios. Experimental results demonstrated that the proposed model achieved stable learning performance and acceptable rainfall prediction accuracy. Overall, the proposed system shows potential for supporting smart irrigation management in peatland plantation areas.

Keywords: Internet of Things (IoT), LSTM, rainfall prediction, peatland, smart irrigation.

1. INTRODUCTION

Indonesia is one of the world's largest palm oil producers, with South Sumatra serving as a major production region [1]. Many oil palm plantations in this area are developed on peatlands, which require proper water management due to their unstable hydrological conditions [2]. Excessive drainage may cause peat subsidence and fire vulnerability, while insufficient drainage can lead to waterlogging and reduced plantation productivity [3]. However, irrigation management in peatland plantations still largely depends on manual observation and fixed scheduling methods, which are inefficient and prone to human error [4]. In addition, climate change has increased the frequency of extreme weather events in tropical regions, further complicating irrigation management in peatland environments [5].

The Internet of Things (IoT) has become an important technology in precision agriculture because of its capability for real-time environmental monitoring through interconnected sensors and wireless communication systems. Previous studies have implemented IoT-based systems for smart irrigation and environmental monitoring [6], [7]. Meanwhile, machine learning methods, particularly Long Short-Term Memory (LSTM), have demonstrated strong performance in time-series forecasting due to their ability to capture temporal patterns from sequential data [5], [8]. The

integration of IoT and LSTM therefore provides significant potential for developing adaptive irrigation systems.

However, limited studies have specifically integrated IoT and LSTM technologies for irrigation optimization in oil palm plantations on tropical peatlands. Therefore, this study proposes an IoT-based weather prediction system utilizing an LSTM model for adaptive irrigation management in oil palm peatland plantations in South Sumatra, Indonesia. The proposed system integrates multiple environmental sensors connected to an ESP32 microcontroller to collect real-time environmental data. The collected data are processed using an LSTM model to generate localized weather predictions for irrigation scheduling[9]. The contributions of this study include: (1) the development of a multi-sensor IoT monitoring system for peatland environments, (2) the implementation of LSTM-based localized weather prediction, and (3) the integration of prediction results into an adaptive irrigation management framework. The remainder of this paper is organized as follows. Section 2 presents the materials and methods. Section 3 discusses the experimental results and evaluation. Finally, Section 4 concludes the paper and provides recommendations for future work.

2. MATERIALS AND METHODS

2.1 SYSTEM ARCHITECTURE AND HARDWARE CONFIGURATION

The proposed system is an IoT-based environmental monitoring and weather prediction system for irrigation optimization in oil palm peatland plantations. Environmental data are collected using multiple sensors connected to an ESP32 microcontroller for real-time monitoring and wireless data transmission [10]. The monitored parameters include soil moisture, rainfall intensity, wind speed, wind direction, temperature, humidity, and atmospheric pressure, which are important indicators for irrigation management in peatland environments.

The collected environmental data are transmitted to a cloud-based database and subsequently processed using a Long Short-Term Memory (LSTM) model to generate localized short-term weather predictions. Due to its capability to capture temporal dependencies in sequential environmental data, the LSTM model is suitable for rainfall forecasting applications. Based on the prediction results and soil moisture conditions, the proposed system determines adaptive irrigation scheduling for peatland plantations.

Furthermore, real-time monitoring data and prediction results are visualized through a monitoring dashboard to support plantation management and decision-making processes. The overall architecture of the proposed system is illustrated in Figure. 1.

The proposed system utilizes soil moisture, rain gauge, anemometer, wind direction, and GY-BME280 sensors to monitor environmental conditions, including soil moisture, rainfall intensity, wind speed, wind direction, temperature, humidity, and atmospheric pressure. The ESP32 microcontroller functions as the main processing and communication unit due to its integrated Wi-Fi capability and suitability for IoT applications. Environmental data collected from the sensors are transmitted wirelessly to a cloud-based database for real-time monitoring and further processing.

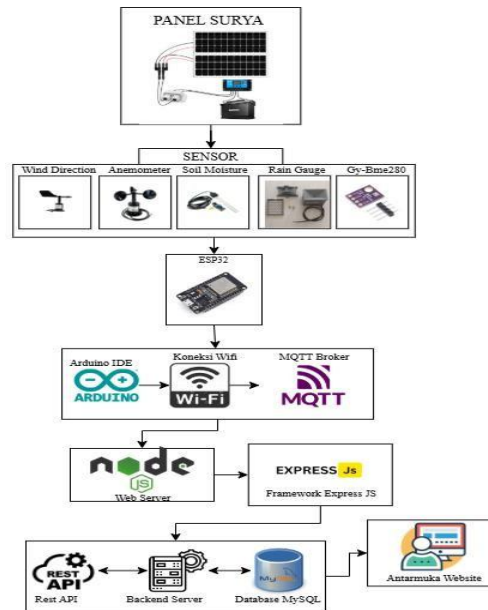


FIGURE 1. Proposed IoT-Based Weather Prediction System Architecture

2.2 DATA ACQUISITION

Environmental data were collected from an oil palm plantation in Palembang, South Sumatra, Indonesia. The proposed system monitored several environmental parameters, including soil moisture, rainfall intensity, wind speed, wind direction, temperature, humidity, and atmospheric pressure using multiple sensors integrated with the ESP32 microcontroller. Sensor data were acquired at one-hour intervals and transmitted wirelessly to a cloud-based database for real-time monitoring and further processing. Initial data visualization was conducted to observe environmental trends and ensure data consistency before model development. The field implementation of the proposed environmental monitoring system is illustrated in Figure 2.



FIGURE 2. Environmental Monitoring Device Deployed in the Oil Palm Plantation Area

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2.3 DATA PROCESSING AND VISUALIZATION

The collected environmental data were processed prior to model development. The preprocessing stage included removing incomplete records, handling missing values using linear interpolation, and applying MinMaxScaler normalization to transform sensor data into a consistent numerical range for time-series analysis. The processed data were organized chronologically and visualized to observe environmental patterns before model training. Examples of environmental data visualization generated from the monitoring system are presented in Figure. 3.



FIGURE 3. Sensor Data Visualization

In addition to visualization analysis, the historical environmental dataset generated by the monitoring system was stored systematically for further processing and model training purposes. The recorded sensor data included timestamps and environmental parameter values collected periodically from the plantation area. An example of the historical sensor dataset utilized in this study is presented in Figure 4.

Waktu	Temp	Humidity	Rain	Wind	Arah
27/12/2025					
06.00.00	21.7	97	0.00	3.8	Barat Laut
05.00.00	21.8	98	0.00	2.0	Barat Laut
04.00.00	22.5	97	0.00	3.3	Barat Laut
03.00.00	24.7	90	0.00	3.9	Barat Laut
02.00.00	25.8	82	0.00	1.7	Barat Laut
01.00.00	27.1	82	0.00	1.4	Barat Laut
00.00.00	27.2	82	0.00	3.0	Barat Laut
23.00.00	29.2	75	0.00	1.8	Barat Laut
22.00.00	29.2	75	0.00	1.6	Barat Laut
21.00.00	30.1	70	0.00	3.0	Barat Laut
20.00.00	31.4	70	0.00	3.4	Barat Laut
19.00.00	30.7	73	0.00	3.6	Barat Laut

FIGURE 4. Sensor Data History Table

The processed and validated dataset was subsequently utilized as input for the LSTM-based weather prediction model to generate localized short-term weather forecasts for adaptive irrigation management in oil palm peatland plantations.

2.4 WEATHER PREDICTION MODEL DEVELOPMENT

In this study, a rainfall prediction model was developed using historical environmental data collected from an oil palm plantation area in Palembang, South Sumatra. The dataset consisted of time-series environmental observations with rainfall (RR) as the target variable. Data preprocessing included date conversion, missing value handling, and MinMaxScaler normalization before arranging the data into seven-day sequential input patterns. The proposed model utilized the Long Short-Term Memory (LSTM) algorithm for time-series rainfall prediction. The model architecture consisted of LSTM, dropout, and dense layers, as presented in Table 1.

TABLE 1.
Structure of the Proposed LSTM Model

Layer	Type	Unit	Keterangan
1	LSTM	128	return_sequences=True
2	Dropout	0.2	Regularisasi
3	LSTM	64	return_sequences=False
4	Dropout	0.2	Regularisasi
5	Dense	32	Aktivasi: ReLU
6	Dense	1	Output Layer

Model training utilized the Adam optimizer with a learning rate of 0.001, Mean Squared Error (MSE) as the loss function, and Mean Absolute Error (MAE) as the evaluation metric. Several forecasting scenarios were implemented, including 24-hour input data for 1–6 hour rainfall prediction, 48-hour input data for 24-hour prediction, 72-hour input data for 24-hour prediction, and 168-hour (7-day) input data for 24-hour prediction. Multiple sequence lengths were implemented during model training and evaluation.. To reduce overfitting, dropout (0.2), early stopping, and ReduceLROnPlateau callback mechanisms were implemented during training. The dataset was divided into training and testing sets using an 80:20 ratio, as presented in Table 2.

TABLE 2.
Training Configuration of the Proposed LSTM Model

Parameter	Value
Epochs	100 (Maximum)
Batch Size	16
Validation Data	Test Set

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To evaluate prediction performance, Root Mean Squared Error (RMSE) and Mean Absolute Error (MAE) were utilized as evaluation metrics. RMSE measures prediction error sensitivity toward large deviations, while MAE measures the average absolute difference between predicted and actual values.

Equation RMSE

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (1)$$

Equation MAE

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i| \quad (2)$$

These evaluation metrics were utilized to measure the prediction accuracy and overall performance of the proposed LSTM model for rainfall forecasting.

In addition to field-collected environmental data, rainfall data obtained from the NASA POWER dataset were also utilized as reference data for comparison and validation purposes. The comparison between sensor-based observations and NASA rainfall data was conducted to evaluate the consistency and reliability of the proposed weather prediction model in representing environmental conditions within the oil palm plantation area.

3. RESULT AND DISCUSSION

3.1 SYSTEM IMPLEMENTATION RESULT

The proposed IoT-based environmental monitoring system was successfully implemented in an oil palm plantation area located in Palembang, South Sumatra. The system integrated multiple environmental sensors with the ESP32 microcontroller to perform real-time environmental monitoring and wireless data transmission.

During implementation, the monitoring system was able to acquire environmental parameters, including soil moisture, rainfall intensity, wind speed, wind direction, temperature, humidity, and atmospheric pressure. The collected data were successfully transmitted to the cloud-based database and visualized through the monitoring dashboard for real-time observation and further analysis. The implementation of the proposed monitoring system in the plantation area is presented in Figure 5.



FIGURE 5. Implementation of the Proposed IoT-Based Environmental Monitoring System

The monitoring dashboard generated by the proposed system is shown in Figure. 6. The dashboard enabled real-time visualization of environmental conditions and facilitated remote monitoring for plantation management purposes.

WAKTU	⌄ SUHU (°C)	⌄ KELEMBAPAN (%)	⌄ HUJAN (MM)	⌄ ANGIN (M/S)	ARAH
📅 Jumat, 12 Desember 2025					16 data
22.00.00	28.0	78	0.00	4.2	↗ Barat Laut
21.00.00	29.7	74	0.00	3.4	↗ Barat Laut
20.00.00	29.6	75	0.00	4.3	↗ Barat Laut
19.00.00	30.6	73	0.00	2.9	↖ Barat
18.00.00	30.2	74	0.00	1.0	↖ Barat
17.00.00	29.1	75	0.00	0.8	↖ Barat
16.00.00	28.7	74	0.00	4.4	↖ Barat
15.00.00	29.1	78	0.00	1.2	↖ Barat
14.00.00	26.7	84	0.00	1.6	↖ Barat
13.00.00	25.5	86	0.00	1.0	↖ Barat
12.00.00	23.5	89	0.00	3.6	↖ Barat
11.00.00	23.1	92	0.00	2.9	↖ Barat
10.00.00	20.9	98	0.00	2.8	↖ Barat
09.00.00	20.6	98	0.00	2.0	↖ Barat
08.00.00	21.1	98	0.00	3.5	↖ Barat
07.00.00	20.2	98	0.00	2.1	↖ Barat

FIGURE 6. Real-Time Environmental Monitoring Dashboard

3.2 ENVIRONMENTAL MONITORING RESULTS

The proposed monitoring system successfully collected environmental data from the oil palm plantation area in real time. Several environmental parameters, including temperature, humidity, rainfall intensity, soil moisture, wind speed, wind direction,

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and atmospheric pressure, were continuously monitored through the deployed sensor network. The collected sensor data were stored as historical environmental records and visualized to observe temporal environmental patterns during the monitoring period. The visualization of historical environmental data generated by the proposed system is presented in Figure 7.

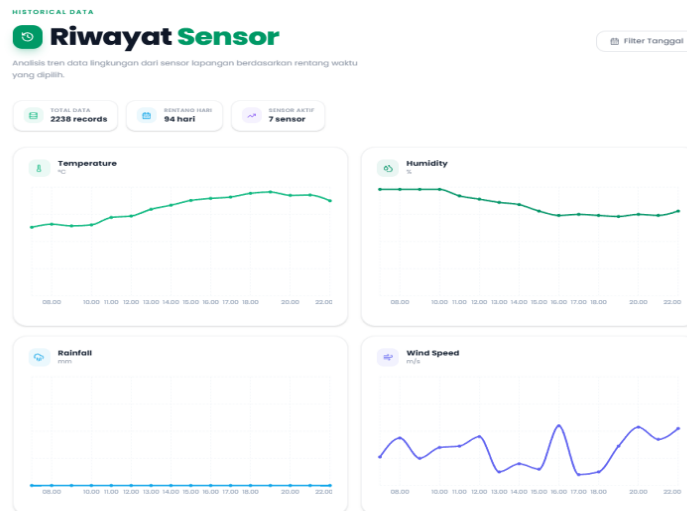


FIGURE 7. Presents the Historical Environmental Monitoring Data Collected from The Proposed System.

The monitoring results demonstrate that the proposed system was capable of performing stable real-time environmental monitoring and continuous environmental data recording for further weather prediction analysis.

3.3 LSTM PREDICTION RESULT

To evaluate the performance of the proposed weather prediction model, several experiments were conducted using historical environmental data collected from the oil palm plantation area. Multiple forecasting scenarios were implemented using different temporal input windows, including 24-hour, 48-hour, 72-hour, and 168-hour observation sequences for short-term rainfall prediction. These scenarios were used to analyze the influence of temporal observation length on rainfall prediction performance.

The training performance of the proposed LSTM model under different prediction scenarios is presented in Fig. 8. Based on the generated learning curves, the model demonstrated stable convergence and relatively low validation loss during the training process. In addition, the implementation of dropout, early stopping, and ReduceLROnPlateau mechanisms contributed to reducing overfitting and improving model generalization performance.

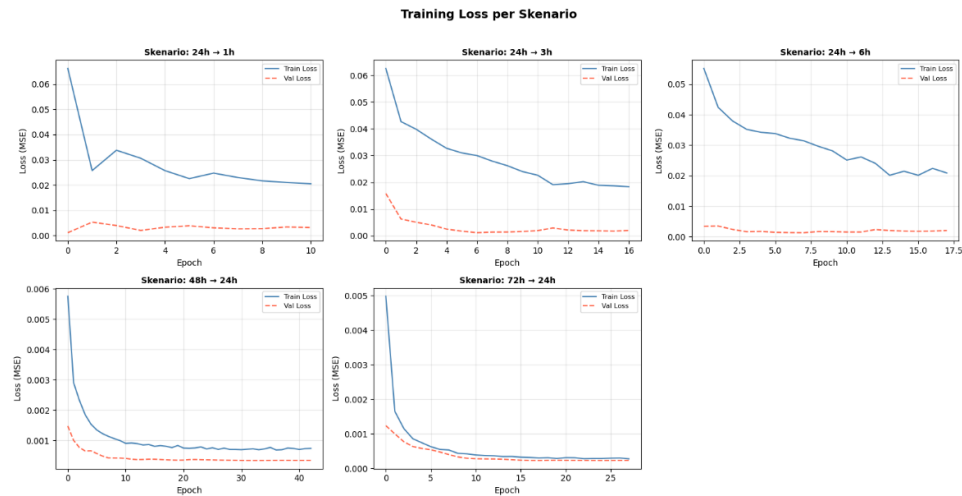


FIGURE 8. Training and Validation Loss Curves for Different Rainfall Prediction Scenarios

The comparison between predicted rainfall values generated by the proposed LSTM model and NASA POWER rainfall data is presented in Figure. 9. The evaluation results indicate that the proposed model was capable of following the general rainfall patterns under different forecasting scenarios.

For short-term prediction scenarios, the model achieved RMSE values of 5.4389 mm for the 24h - 1h scenario, 5.3299 mm for the 24h - 3h scenario, and 2.9569 mm for the 24h - 6h scenario. Meanwhile, longer observation windows achieved RMSE values of 3.2204 mm for the 48h - 24h scenario and 3.2152 mm for the 72h - 24h scenario.

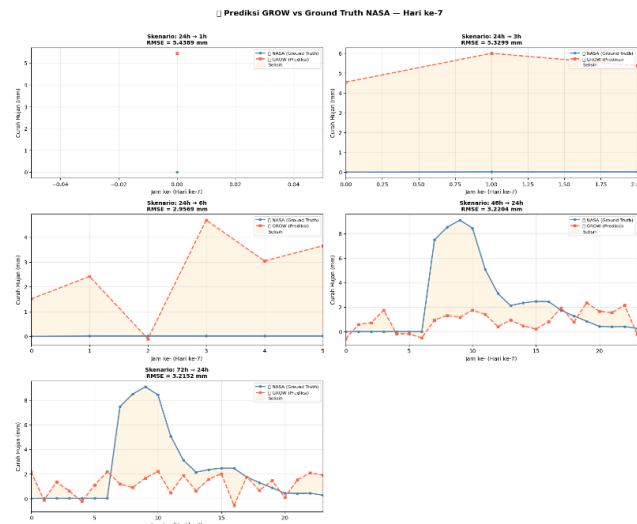


FIGURE 9. Comparison Between Actual and Predicted Rainfall Values Using the LSTM Model

4. CONCLUSION

This study proposed an IoT-based environmental monitoring and rainfall prediction system for irrigation optimization in oil palm peatland plantations. The

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proposed system successfully performed real-time environmental monitoring using multiple sensors integrated with an ESP32 microcontroller. Furthermore, the implemented LSTM model demonstrated acceptable short-term rainfall prediction performance under multiple forecasting scenarios. Overall, the proposed system has potential to support adaptive irrigation management and environmental monitoring in peatland plantation areas.

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