11th LIS International Conference
Liga Ilmu Serantau 2025

ISSN: 2985-4393

The Development of Solar-Powered IoT Environmental Station on Pulau Tengah, Mersing, Johor.

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Abstract. Remote island ecosystems require continuous environmental monitoring to support biodiversity conservation; however, such environments often lack stable power supply and communication infrastructure. Pulau Tengah, located off the coast of Mersing, Johor, Malaysia, is a biodiversity hotspot and an important sea turtle nesting site where manual monitoring methods remain limited and discontinuous. This study presents the design, development, and field deployment of a solar-powered Internet of Things (IoT) environmental monitoring station under the Sustainable Project for IoT Environmental Station (SPIES) initiative. The system integrates multiple sensors for temperature, relative humidity, air quality, and wind speed, controlled by an ESP32 microcontroller and powered by a standalone photovoltaic subsystem. Environmental data are transmitted in real time to the Blynk IoT cloud platform for remote monitoring and analysis. The prototype was deployed for four weeks, during which continuous environmental data were successfully recorded. Results indicate that the system captured realistic tropical island environmental variations and maintained stable operation under off-grid conditions. The findings demonstrate the feasibility of renewable-powered IoT environmental monitoring systems for remote island ecosystems and highlight their potential application in long-term ecological and conservation studies.

Keywords: Solar-Powered IoT, Environmental Monitoring, Remote Island Ecosystems, Smart Weather Station, Off-Grid Renewable Energy.

1. INTRODUCTION

Remote island ecosystems are ecologically valuable but environmentally fragile. Pulau Tengah, located off the coast of Mersing, Johor, as shown in Figure 1 is a biodiversity hotspot and an important nesting site for endangered sea turtles. Previous studies have shown that temperature and humidity play critical roles in determining hatchling sex ratios and survival rates [1], [2]. Manual nest monitoring, however, is often labor-intensive, sporadic, and unable to provide continuous real-time data [3].

To overcome such limitations, recent advances in the Internet of Things (IoT) and renewable energy have made it possible to design autonomous environmental monitoring stations. IoT-enabled smart weather stations allow real-time data acquisition and transmission from remote or off-grid areas [4], [5]. Low-cost prototypes have been developed for diverse applications, ranging from urban climate studies [7] to agricultural and ecological monitoring [6]. However, many of these systems are deployed in accessible areas and rarely in small island contexts where connectivity and power access are challenging.

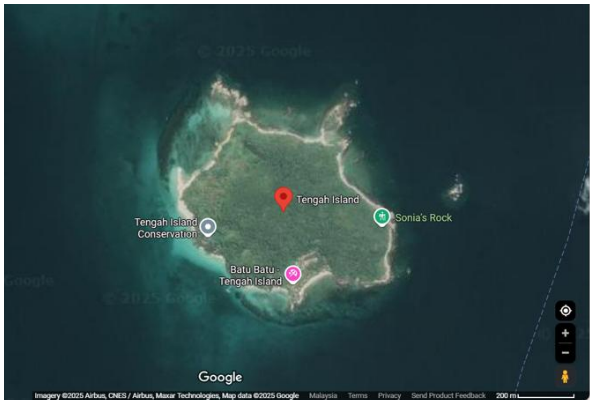

Figure 1. Satellite view of Pulau Tengah, Mersing, Johor, Malaysia, the deployment site for the IoT-Based Environmental Station. *(Source: Google Maps, Imagery ©2025 Airbus, CNES / Maxar Technologies.)*

Several works demonstrate the applicability of IoT systems in conservation and remote monitoring contexts. Solar-powered IoT systems have been implemented for endangered bird monitoring in isolated habitats [8]. Renewable-powered off-grid monitoring solutions have also been reported for remote environmental applications in northern Finland [9]. Wireless sensor networks have been identified as transformative tools for environmental and earth system science, particularly in harsh and distributed environments [10]. Nevertheless, there remains a gap in the application of IoT-enabled environmental stations within tropical island ecosystems where continuous and reliable environmental data are essential for conservation planning.

This paper presents the development and deployment of a solar-powered IoT environmental station on Pulau Tengah under the SPIES project. The system integrates sensors for temperature, humidity, wind speed, wind direction, rainfall, light intensity, and air quality, with data transmitted in real-time via the Blynk IoT platform. The goal is to demonstrate the feasibility of IoT-enabled, renewable-powered monitoring in an off-grid island environment, and to support ecological research and conservation.

2. LITERATURE REVIEW

Environmental conditions play a critical role in sea turtle nesting success. Incubation temperature has been shown to determine hatchling sex ratios [1], while extreme nest temperatures significantly reduce survival rates [2]. Furthermore, manual monitoring methods have been reported to miss short-term environmental fluctuations, limiting the accuracy of ecological assessments [3]. These findings highlight the importance of continuous and reliable environmental data collection.

IoT-enabled weather stations have emerged as effective solutions for automated environmental monitoring. Recent innovations integrate multiple sensors with low-power communication systems to enable real-time data acquisition [4]. Solar-powered IoT weather stations have demonstrated suitability for off-grid environments through real-time visualization and remote accessibility [5]. Additionally, IoT systems incorporating air quality sensors such as the MQ135 have been developed for low-cost environmental applications [6]. Portable IoT stations have also been validated against commercial monitoring systems, confirming that cost-effective implementations can achieve acceptable measurement performance [7].

The application of IoT technologies in remote and conservation-oriented contexts further demonstrates their potential. Solar-powered IoT monitoring systems have been deployed for wildlife conservation in isolated habitats [8]. Renewable-powered off-grid monitoring platforms have also been implemented in remote visitor centers and harsh environmental conditions [9]. Low-cost automatic weather stations within IoT frameworks have shown scalability for distributed monitoring applications [11]. Environmental sensor networks have been identified as

 ISSN: 2985-4393

transformative tools for earth system science, particularly in remote and distributed environments where continuous data acquisition is essential [**10**].

Despite significant advancements, limited research has focused on the deployment of IoT-enabled environmental stations in tropical island ecosystems. In such environments, biodiversity conservation efforts, including sea turtle nesting management, depend on precise and continuous environmental monitoring. The SPIES project addresses this gap by developing and deploying a solar-powered IoT environmental station at Pulau Tengah, Mersing, Johor.

3. RESEARCH METHODOLOGY

This study employed a design–development–deployment approach. The environmental station was developed as a solar-powered, IoT-enabled system to continuously monitor environmental parameters at Pulau Tengah, Mersing, Johor. The design emphasized low-cost components, renewable energy integration, and real-time data transmission.

3.1 Overall System Architecture

Figure 2 illustrates the overall architecture of the solar-powered IoT environmental monitoring system developed under the SPIES project. The system consists of three main subsystems: the environmental sensing unit, the processing and communication unit, and the cloud-based monitoring platform.

The environmental sensing unit integrates multiple sensors, including the DHT22 temperature and humidity sensor, MQ135 gas sensor for air quality monitoring, an anemometer for wind speed measurement, a wind vane for wind direction detection, a raindrop sensor for rainfall detection, and an LDR sensor for light intensity measurement. All sensor outputs are connected to the ESP32 microcontroller, which serves as the central processing unit. Real-time readings are also displayed locally through an LCD module using the I2C communication interface.

The ESP32 transmits processed environmental data via its built-in Wi-Fi module to the Blynk IoT cloud platform. The platform enables real-time visualization and remote monitoring through smartphones and laptops. Data can also be exported for further analysis using spreadsheet software.

Although the complete system integrates six environmental sensors, this paper focuses specifically on four parameters: Temperature (DHT22), Relative Humidity (DHT22), Air Quality (MQ135); and Wind Speed (Anemometer). These parameters were selected to evaluate the environmental monitoring capability of the system under tropical island conditions.

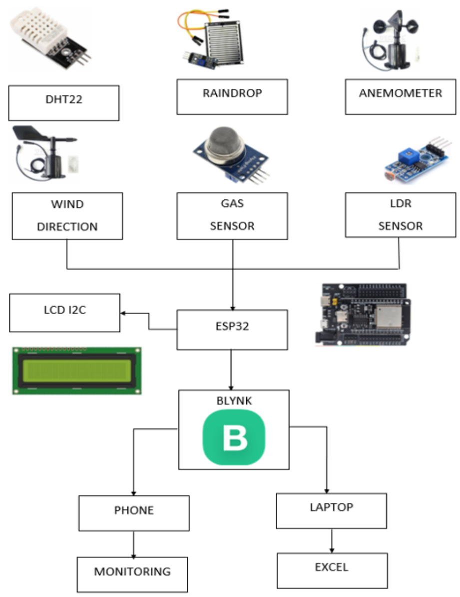

Figure 2. System Architecture of SPIES Prototype.

3.2 Hardware Integration and Power System

Figure 3 presents the detailed hardware wiring configuration and power management system of the environmental station. The sensing modules are directly interfaced with the ESP32 microcontroller through analog and digital input pins. The DHT22 sensor provides calibrated digital outputs for temperature and humidity. The MQ135 gas sensor generates analog voltage signals corresponding to relative gas concentration levels. The anemometer produces pulse signals proportional to wind speed, which are processed by the ESP32 to determine wind intensity.

The system is powered by a standalone solar energy subsystem consisting of a photovoltaic panel, a solar charge controller, and a rechargeable battery. The solar panel converts solar radiation into electrical energy, which is regulated by the charge controller and stored in the battery to ensure continuous operation. The stored energy supplies stable DC voltage to the ESP32 and all connected sensors.

This solar-powered configuration enables autonomous operation in an off-grid environment, which is critical for deployment at Pulau Tengah, where conventional power infrastructure is unavailable. The design ensures sustainable operation, reduced maintenance requirements, and long-term environmental monitoring capability.

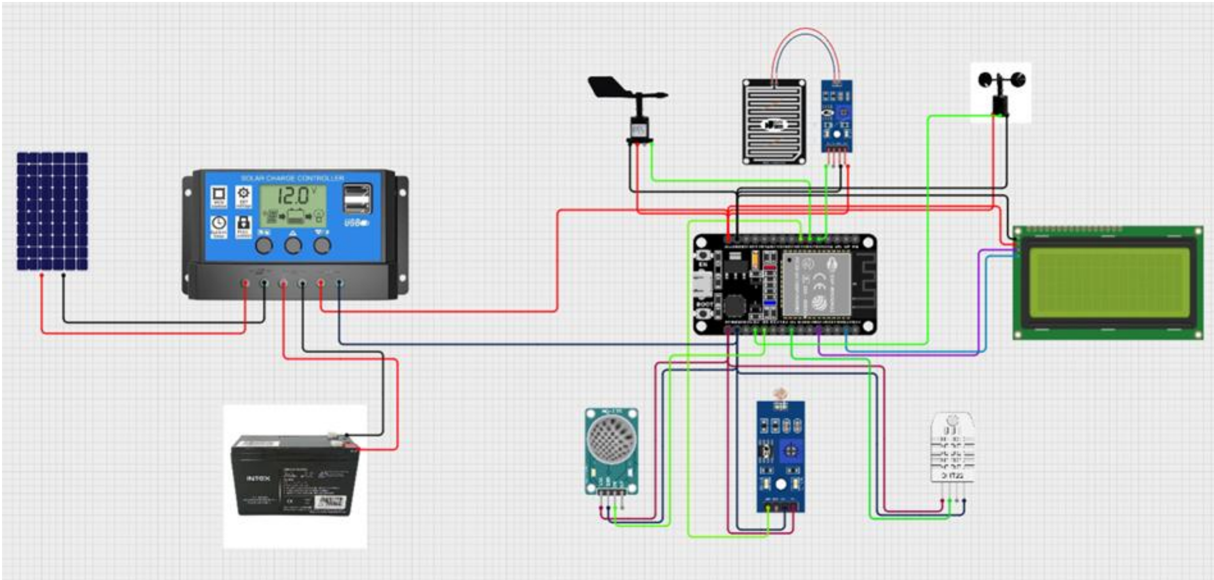

Figure 3. Schematic Diagram of SPIES prototype

3.3 Data Collection Methods

The prototype station was deployed on Pulau Tengah in July 2025. Environmental data were collected continuously for a period of four weeks, covering parameters of temperature, humidity, wind speed, rainfall, and air quality. Data were logged onto the IoT platform for real-time access and later exported for analysis.

3.4 Analytical Techniques

The collected data were analyzed using descriptive statistics and graphical visualization. Trends were examined to evaluate system performance and environmental variability. Sensor readings were compared against reference ranges from literature to assess accuracy. System reliability was evaluated in terms of power autonomy, connectivity stability, and data consistency throughout the deployment period.

4. RESULTS

This section presents the environmental data collected by the solar-powered IoT environmental station deployed at Pulau Tengah, Johor, during July 2025. The analysis focuses on four key environmental parameters discussed in this paper: temperature, relative humidity, air quality (MQ135 sensor), and wind speed. These parameters were selected to evaluate the station's monitoring capability and to represent typical tropical island environmental conditions. The recorded data demonstrate daily and short-term variations consistent with coastal tropical weather dynamics. In addition to environmental trends, system performance in terms of solar power autonomy, data transmission reliability, and sensor stability was also observed throughout the deployment period. The following subsections describe each parameter in detail.

4.1 Temperature Trends

The IoT environmental station successfully recorded daily temperature variations at Pulau Tengah throughout July 2025. As illustrated in Figure 4, the measured temperature values ranged from 27 °C to 41 °C, reflecting typical tropical coastal conditions at Pulau Tengah, Johor. The highest temperature (~41 °C) was observed on 30 July 2025, while the lowest temperature (~27 °C) occurred on 2 July 2025. Daily fluctuations were evident, with moderate increases during mid-to-late July, followed by a slight decrease toward the end of the monitoring period. The error bars shown in Fig. 2 represent sensor variability and indicate acceptable measurement consistency throughout deployment.

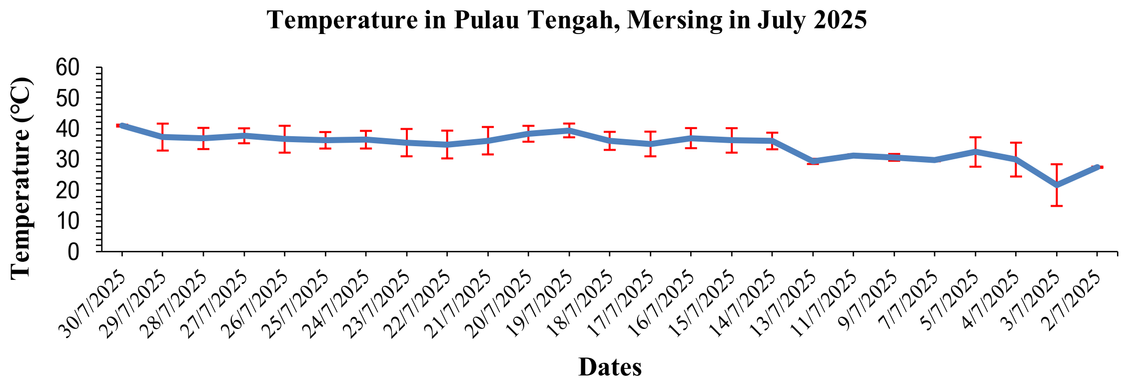

Figure 4. Daily temperature trends recorded by the IoT environmental station at Pulau Tengah, Johor, Malaysia during July 2025.

The mean daily temperature recorded during the monitoring period was approximately 34.8 °C, with a standard deviation of ±3.9 °C, indicating moderate thermal variability typical of tropical island environments. These variations correspond to diurnal heating patterns and coastal atmospheric dynamics. The observed temperature range is consistent with reported environmental conditions in equatorial maritime regions and confirms the capability of the developed system to capture realistic environmental fluctuations.

4.2 Relative Humidity Variations

The IoT environmental station continuously monitored relative humidity (%RH) throughout July 2025 at Pulau Tengah. As illustrated in Figure 5, the recorded humidity values ranged between 5% and 85% RH, indicating substantial short-term environmental variability typical of tropical island climates. The highest humidity levels (approximately 80–85% RH) were observed on 2 and 3 July 2025, likely associated with rainfall events or elevated atmospheric moisture content. Conversely, the lowest recorded values (approximately 5–10% RH) occurred during mid-July, suggesting transient dry conditions potentially influenced by increased solar radiation and reduced precipitation.

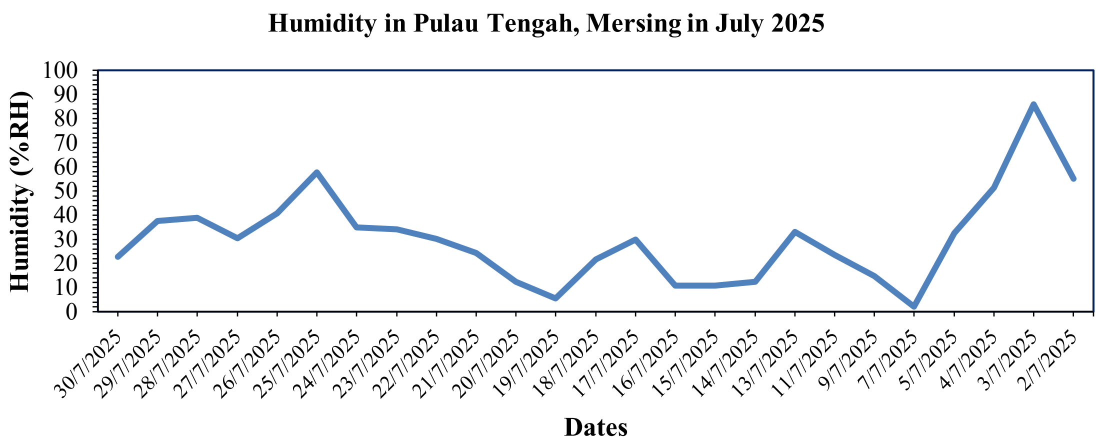

Figure 5. Relative humidity (%RH) variations measured by the IoT environmental station at Pulau Tengah, Johor, Malaysia during July 2025.

The mean relative humidity recorded during the monitoring period was approximately 32.6% RH, with a standard deviation of ±21.4% RH, indicating high variability across the sampling duration. The relatively large standard deviation confirms the system’s ability to capture significant atmospheric transitions rather than producing static or saturated readings.

Overall, the humidity dataset demonstrates the responsiveness and sensitivity of the DHT-type sensor integrated into the IoT environmental station, validating its suitability for deployment in fluctuating tropical coastal environments.

4.3 Air Quality Monitoring

Air quality measurements were obtained using the MQ135 gas sensor integrated into the IoT environmental station. The sensor recorded values ranging between 8 and 25 raw sensor units during July 2025, as shown in Figure 6. These values represent relative sensor responses rather than absolute pollutant concentrations. Although the MQ135 sensor is capable of estimating gas concentrations in parts per million (ppm) when calibrated against known reference gases, laboratory calibration was not performed in this deployment. Therefore, the results are presented in raw sensor units to reflect relative variations and trend analysis instead of quantitative pollutant levels.

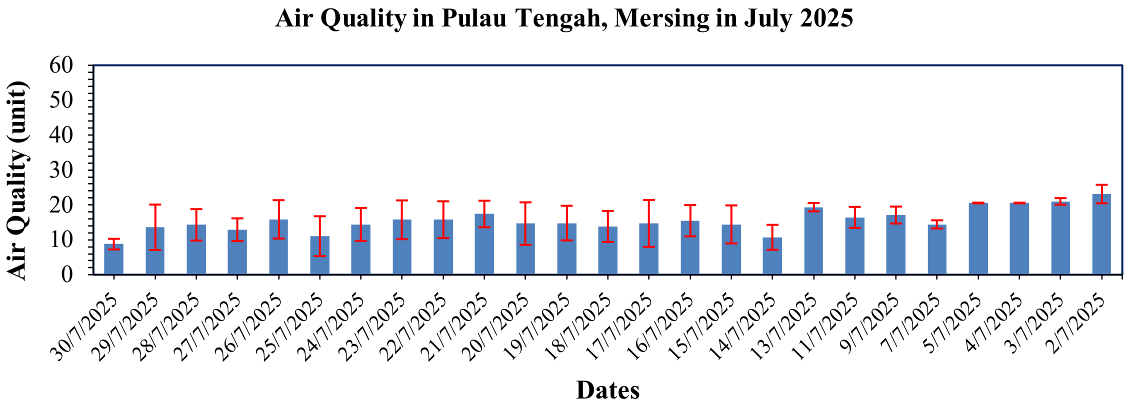

Figure 6. Air quality index values (MQ135) measured by the IoT environmental station at Pulau Tengah, Johor, Malaysia during July 2025.

The mean air quality reading during the monitoring period was approximately 16.4 raw units, with a standard deviation of ±4.8 units. The moderate standard deviation indicates observable variability in atmospheric conditions over time while maintaining stable sensor performance.

The recorded data indicate moderate day-to-day variability, with a gradual increase in sensor readings observed toward the end of July. This trend may be associate indicate changes in atmospheric conditions, including increased particulate matter, higher humidity interaction, or localized environmental activities. Short-term fluctuations observed in the dataset further demonstrate the sensor's responsiveness to environmental changes. Despite the limitation of non-calibrated measurements, the MQ135 sensor successfully captured temporal variations in air quality, supporting the feasibility of integrating low-cost gas sensors within a solar-powered IoT monitoring framework for remote island environments.

4.4 Wind Speed Data

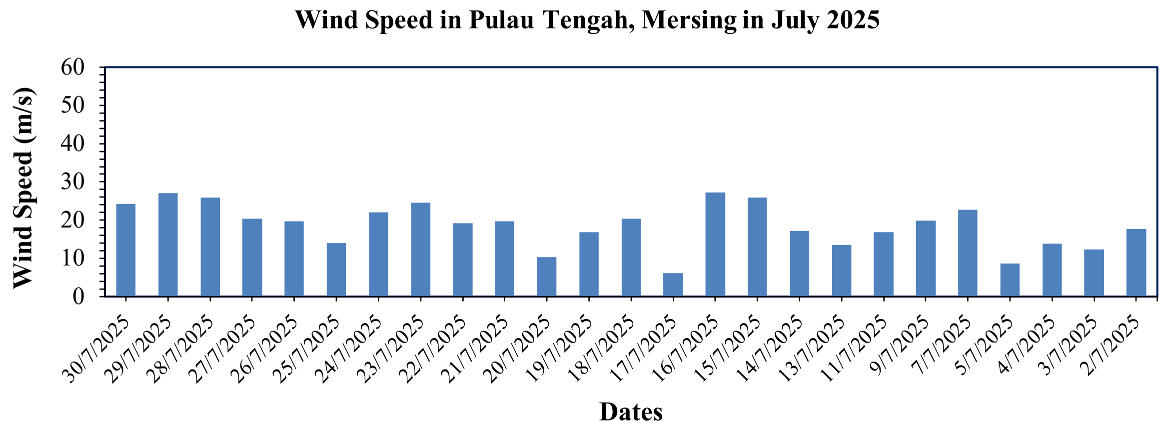

Figure 7. Wind speed variations (m/s) recorded by the IoT environmental station at Pulau Tengah, Johor, during July 2025.

Wind speed data were continuously recorded using an anemometer integrated into the IoT environmental station. As presented in Figure 7, wind speed values ranged between 6 and 28 sensor units throughout the July 2025 monitoring period. Peak wind speed values were observed on 16 July and 29 July, indicating periods of stronger coastal airflow, while lower readings were recorded during relatively calm atmospheric conditions. The dataset reveals noticeable day-to-day variability, reflecting typical coastal wind dynamics influenced by sea-breeze circulation and localized atmospheric pressure changes.

5. DISCUSSION

The results demonstrate that the solar-powered IoT environmental station successfully monitored environmental conditions at Pulau Tengah, Mersing during the deployment period. The recorded data reflect realistic tropical island characteristics and confirm the system's operational stability. Temperature measurements ranged from 27 °C to 41 °C, with a mean value of 34.8 °C. These values are consistent with tropical coastal climates where high solar radiation contributes to elevated daytime temperatures. The moderate standard deviation indicates normal daily fluctuations rather than irregular sensor behavior.

Relative humidity showed high variability, ranging from 5% to 85% RH, with a mean of 32.6% RH. The large standard deviation suggests rapid environmental transitions, likely influenced by rainfall events, sea-breeze circulation, and evaporation cycles. The system successfully captured these dynamic changes. Air quality reading ranged between 8 and 25 raw units, with a mean value of 16.4 units. Although the MQ135 sensor was not calibrated into ppm values, the dataset shows observable variation over time. This confirms the sensor's ability to detect relative atmospheric changes, though future calibration is required for quantitative analysis.

Wind speed ranged from 6 to 28 units, with a mean of 17.2 units. The wide variation indicates dynamic coastal wind behavior, which is typical for small island environments. Wind conditions are influenced by surrounding open water and temperature differences between land and sea during the day and night. In terms of system performance, the solar-powered subsystem sustained continuous operation throughout the monitoring period. Data transmission through the Blynk platform was generally stable, with only minor connectivity interruptions. These findings confirm the feasibility of deploying a renewable-powered IoT monitoring system in a remote, off-grid island setting.

6. CONCLUSION

This study presented the design and deployment of a solar-powered IoT environmental station on Pulau Tengah, Johor. The station successfully measured key parameters including temperature, humidity, air quality, wind speed, rainfall, and light intensity, with real-time data transmission via the Blynk platform. Results showed that the system was able to capture meaningful environmental variations consistent with tropical island conditions.

The findings demonstrate that IoT-enabled, renewable-powered monitoring systems can operate reliably in off-grid island environments, providing continuous data that conventional manual methods cannot achieve. While air quality and wind sensors provided useful relative data, further calibration is needed to ensure accuracy in standard units such as ppm or AQI. Connectivity interruptions also suggest the need to explore alternative communication protocols such as LoRaWAN or satellite IoT.

Overall, the SPIES project confirms the feasibility of portable, solar-powered IoT weather stations for environmental and biodiversity monitoring in remote ecosystems. Future work will focus on sensor calibration, communication improvements, and scaling deployment to other conservation sites.

ACKNOWLEDGMENTS (OPTIONAL)

The authors would like to gratefully acknowledge the Jabatan Pendidikan Politeknik dan Kolej Komuniti (JPPKK) for supporting this research under the TVET Applied Research Grant Scheme (T-ARGS), Grant No. T-ARGS/2025/BK04/00455. The authors also extend their appreciation to Tengah Island Conservation (TIC) for their valuable collaboration, logistical assistance, and access to the field site during the data collection period. In addition, sincere thanks are given to Politeknik Mersing (PMJ) for providing technical support, institutional facilities, and administrative coordination throughout the implementation of this project.

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