IoT-Based Real-Time Monitoring System for Sea Turtle Nesting on Tengah Island, Mersing, Johor

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Abstract. Manual monitoring of conventional nesting sea turtles presents several drawbacks, such as being time-consuming, invasive in nature, and providing low-resolution data for conservationists. Hence, an online monitoring-based system integrated with the Internet of Things (IoT) is essential to address the aforementioned issues. The current study developed a non-invasive and real-time sea turtle nest monitoring system. The system consists of a low-power remote sensing device (Nest Node) and a data portal (Station Node), connected through a LoRa wireless network. The IoT system was utilised to monitor internal nest environments during the first week of incubation (day 1, day 2, day 5, and day 7), recording data on environmental parameters such as temperature, humidity, air pressure, carbon dioxide (CO_2), oxygen (O_2) levels, and structural vibrational activity. Data were continuously logged and transferred to a cloud-based server for real-time analysis. Preliminary results indicate that sand insulation, along with limited airflow, quickly stabilized the internal temperature and moisture levels within the nest, with these same mechanisms being responsible for the observed effect. In addition, the inverse trend between CO_2 and O_2 levels was found to correlate with increased vibrational activity, suggesting heightened embryonic metabolism and potential hatching movement. These findings demonstrate the system's capability to extract vital environmental and biological data, offering a functional tool for the conservation of sea turtle species and other environmental monitoring applications.

1 Introduction

Sea turtles, species that have cohabitated the world's seas with humans for over 100 million years, are responsible for maintaining the balance of marine environments. They are crucial to the health of coral reefs and seagrass meadows, both of which support critical habitats for a host of marine species. Of all the different steps in the sea turtles' life cycles, the nesting stage is particularly vulnerable and central to the long-term health of their populations. The

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proper formation of embryos and the survival of hatchlings depend on specific conditions in the nest environment, such as temperature, humidity, levels of oxygen (O_2) and carbon dioxide (CO_2), and physical stability of the sand structure (vibrations) [1].

Over the past decades, populations of sea turtles have decreased because of human-induced threats such as coastal development, plastic pollution, illegal poaching, and climate change impacts. Global warming, for instance, affects the temperature of the sand in nesting beaches, potentially disrupt the sex ratio of hatchlings due to temperature-dependent sex determination (TSD) [2]. Temperature is also one of the most important determinants of sea turtle incubation, and optimal thermal windows differ among species. Successful incubation in the green sea turtle (Chelonia mydas) usually falls within the range of 26°C to 34°C, with the sex of the hatchlings being decided by an about 29°C pivotal temperature [3]. Also with an identical range is the hawksbill turtle (Eretmochelys imbricata) but with somewhat higher pivotal temperatures closer to 30°C [4]. Similarly important to embryo development among all species is nest humidity that controls the exchange of the gases and inhibits desiccation of the eggs [5]. High hatching success can only be guaranteed if the sand remains moist to an appreciable extent because very dry and excessively moist sand extremes turn out to be adverse to the embryos [6].

There must be enough oxygen (O_2) for embryonic respiration. Low oxygen levels, particularly in packed or compacted sand, may lead to hypoxia [7]. Average O_2 concentrations in a sea turtle nest start out at atmospheric (~21%) but can decline markedly during the final third of incubation when metabolic demand is highest. CO_2 concentrations, which are inversely proportional to oxygen levels, increase as embryos respire. CO_2 levels of up to or more than 5% could affect the normal development of embryo and retard hatching [7].

The vibrations in the nest chamber can indicate embryonic movement, hatching activity, or external disturbances. Piezoelectric sensors measure small changes in the structure of the nest, from which conservationists also estimate hatchling emergence timing. Despite the biological significance of these parameters, most existing monitoring techniques are based on labour-intensive manual nest inspections that can be invasive and are clearly not adequate for real-time data collection [8]. In this work a non-invasive, IoT-based monitoring system is introduced to monitor such vital environmental parameters in real time and in situ, with the aim of enhancing conservation strategies and long-term data collection in remote island environments such as Tengah Island.

Tengah Island in Johor, Malaysia is a nesting site for endangered species, the green sea turtle and the hawksbill turtle. This beach represents important conservation areas; however, they are often remote and understudied because of limitations in monitoring resources and accessibility. As illustrated in Fig. 1, the island's geographic isolation and ecological sensitivity make it an ideal yet logistically challenging site for sea turtle conservation and environmental monitoring activities.

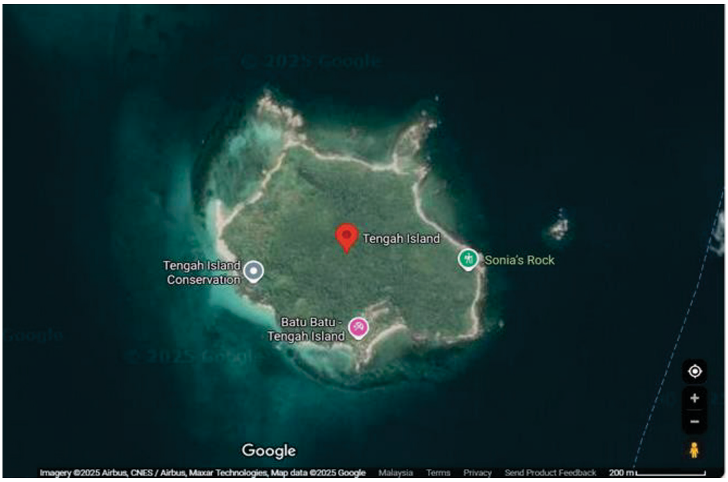

Fig. 1. Satellite view of Pulau Tengah, Johor, Malaysia, a nesting site for endangered sea turtles. The image highlights the island's remote location and its conservation zones, including Tengah Island Conservation and Tunku Abdul Jalil Conservation Centre. (Source: Google Maps, Imagery ©2025 Airbus, CNES / Maxar Technologies.)

As shown in Fig. 2, current conservation strategies methods rely on manual nest checks and periodic measurements, which are time-consuming, may be intrusive, and provide limited information. Furthermore, the inaccessibility of most nesting locations presents logistical complications to regular data recovery and power supply for continuous monitoring systems. The development of Internet of Things (IoT) technology has enabled us to deploy compact, low- power sensors capable of collecting environmental data continuously and non-invasively [9]. These systems are particularly useful in remote field conditions where normal power infrastructure is unavailable. However, the application of such IoT-based tools in marine conservation, more specifically, in the delicate microenvironment of turtle nests, remains underexplored [10].

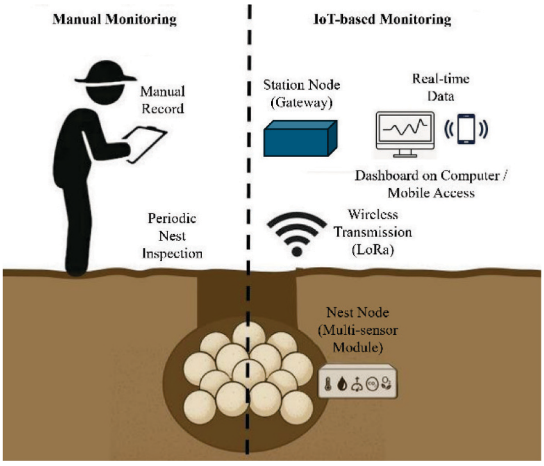

Fig. 2. Comparison between the manual and IoT-based monitoring of sea turtle nests.

This study presents a portable IoT-based real-time monitoring system that is designed to measure critical environmental parameters inside sea turtle nests, such as temperature, humidity, pressure, carbon dioxide (CO_2), oxygen (O_2), and nest structure vibrations. The system is powered by a rechargeable lithium battery to facilitate easy deployment in off-grid island environments. By comparing the surface and nest environments, the system offers insights into the nesting environment with relevance to conservation operations and scientific studies.

2 Literature Review

Recent advances in Internet of Things (IoT) technologies significantly improved the monitoring and observation on environmental and ecological parameters. IoT-enabled smart sensors are increasingly used to acquire and transmit environmental data from the remote and inaccessible sites. Their applications under the umbrella of sustainable agriculture and ecological management are prominent through the capability to implement non-invasive and real-time monitoring systems.

Internet of things techniques are now also highly popular for the functions in maritime conservation. To date, various studies have been conducted on the online monitoring of sea turtle populations and their habitats, focusing on the efficiency of unmanned systems [11–12]. In addition, advancements in marine biology have been driven by the revolution in sensor technology and its integration with genetic research, promoting a stronger connection between innovation and conservation efforts. Meanwhile, frontier knowledge arising from significant advancements in IoT-based environmental monitoring experiments has provided reliable data for ecological research.

While current studies provide considerable support for IoT adoption for environmental applications, these studies mostly relate to large-scale or surface-level monitoring systems [13-14]. Nevertheless, this study proposes an innovative IoT platform that can monitor nest conditions in sea turtle hatcheries. Embedding compact sensors directly beneath nesting sites allows this system to capture environmental parameters (temperature, humidity, pressure, CO_2, and oxygen) and activity parameters (vibration) that are often overlooked in broader ecological monitoring programs. Moreover, the use of LoRa-based wireless communication allows for the streaming of data over long distances under remote, off-grid island conditions, an aspect not highly highlighted from previous studies.

Therefore, this research extends previously established frameworks but adds an original contribution to the literature by emphasising real-time, in-situ acquisition of ecological data within the fragile micro-environment of sea turtle nests, filling a gap between marine biology and applied environmental IoT.

3 Methodology

This section outlines the methodology for a preliminary, proof-of-concept field trial of a novel IoT system. The system is designed for the non-invasive, in-situ environmental monitoring of sea turtle nests. The main objective of this initial study is to validate the system's architecture, data integrity, and operational longevity in a field environment over a multi week period.

3.1 System Architecture

The monitoring system was architected based on two-node, star network topology to optimise for low-power remote operation and reliable data backhaul as depicted in Fig. 3. This architecture consists of a remote sensing unit, designated the "Nest Node", while a data-aggregating gateway unit, designated the "Station Node".

The Nest Node functions as a self-contained, battery-powered slave device that is designed for placement within the nest environment. Its function is to periodically capture the key environmental parameters and transmit them wirelessly. The Station Node will act as a main powered master gateway, that responsible for receiving data from the Nest Node, capturing its own environmental data, and relaying all aggregated information to a cloud database for storage and analysis. To be specific, the vibration sensor which was attached in the nest node will collect the signal i.e., both environmental parameters and activity signals. Meanwhile, LoRa network was used as a medium for signal transmission for the measured data (sensor to nest node). The measured data was then stored in the cloud.

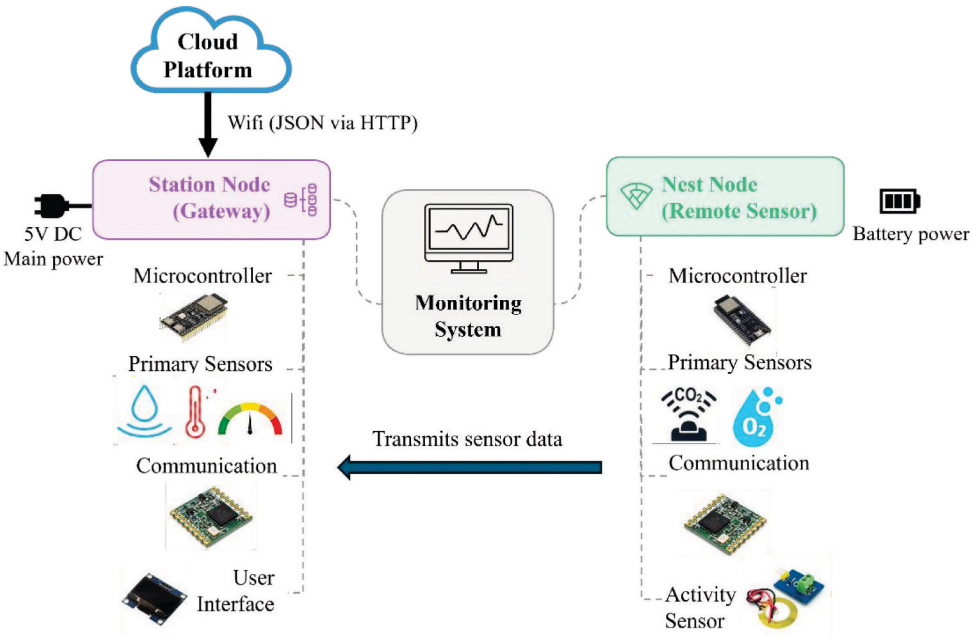

Fig. 3. System Architecture and Data Flow Diagram.

The Nest Nodes will send the sensor measurements data through LoRa to the Station Nodes, which was then upload the compiled measurements to a cloud database by means of WiFi. The overall components used in the node is tabulated in Table 1. With regards to functionality, the Station Node is equipped with high-end communication as well as data acquisition features, whereas the Nest Node is designed with low power consumption as well as high accuracy.

Table 1. Component Specifications for Monitoring Nodes

Component	Station Node (Gateway)	Nest Node (Remote Sensor)
Microcontroller	ESP32-S3 Dev Board	WEMOS S2 Mini (ESP32-S2)
Primary Sensors (Environmental Sensors)	Temperature, Humidity, Pressure Sensor (Bosch BME280)	CO_2 Sensor, O_2 Sensor, Temperature, Humidity, Pressure Sensor
Activity Sensor	N/A	Piezoelectric Vibration Module
Communication	LoRa, WiFi	LoRa
Power System	5V DC Mains Power	Li-ion Battery, Charger, MOSFET Power Gate
User Interface	OLED Display	N/A

3.2 Sensor Calibration and Field Deployment

System calibrations were carried out to ensure accuracy of the collected data. The Nest Node is covered with a waterproof and permeable material, and was carefully placed within the sand adjacent to a nesting clutch of sea turtle eggs. The depth of placement was matched with that of the midpoint of the nest of eggs to acquire the most representative data regarding subterranean nest environment with minimal physical disturbance. The Station Node was stationed approximately 150 meters away from the nesting site, placed in a location with good power supply stability as well as reliable WiFi signal coverage.

Prior to deployment, critical sensors were calibrated. The O_2 Sensor was given a single-point calibration in open fresh air in order to establish a base reading that corresponds to 20.9% standard atmospheric oxygen concentration. The Automatic Self-Calibration (ASC) feature of the CO_2 Sensor was activated through placing the node in a well-ventilated outdoor environment for 24 hours. This served to allow the sensor to calculate a reliable base compared to the ambient atmospheric CO_2 concentration (about 420 ppm). The Bosch BME280 was used as is, reliant on its factory calibration. The piezoelectric vibration sensor's calibration involved defining a base signal threshold from quiescent readings, which made it possible to readily detect anomalous vibration events that signal hatching activity.

3.3 Data Acquisition and Transmission Protocol

To ensure system efficiency and updated on the current data, time-based schedule was implemented in the developed system. To be specific, the Nest Node will be triggered for every two hours. Upon operating, MOSFET power gate will be activated. In this period, all reading is collected and transmitted. The Station Node was designed to configure and acquire the data from its local BME280 sensor for every hour. Besides, JavaScript Object Notation (JSON) format was employed to transmit the packaged the data that obtained from the sensors. This is to ensure data integrity and for ease of analysing by the receiving node and the cloud endpoint. Of note, the LoRa protocol was selected for the signal transmission due long-range and low- power characteristic [15].

3.4 Data Management and Cloud Integration

All collected data was aggregated by the Station Node and relayed to a cloud-based spreadsheet for persistent storage and subsequent analysis. For this preliminary study, a Google Sheets spreadsheet served as the time-series database. A custom Google Apps Script was developed to function as a web endpoint, receiving data from the Station Node via HTTP GET requests. This script was responsible for parsing the incoming JSON data and appending it as a new row in the structured spreadsheet.

The Station Node buffered all received LoRa data and its own local sensor readings in its volatile memory. Once every hour, it started a connection to the local WiFi network. During this process, the internal clock was synchronized with a Network Time Protocol (NTP) server. This ensured that every data point uploaded to the cloud was appended with an accurate, globally synchronized timestamp. Following a successful time sync, the node would upload its entire data buffer to the Google Sheet and then clear the buffer to begin the next collection cycle. As a result of this protocol, a comprehensive dataset with a clear temporal resolution was obtained, containing discrete measurements from both the remote and gateway nodes every hour.

3.5 Measurement Procedure

The on-site surface measurements were carried out to obtain the reference data. Three parameters i.e., temperature, humidity, and pressure are considered in this study. These data were collected during the first week of incubation (day 1, day 2, day 5 and day 7). Besides that, parameters such as carbon dioxide (CO_2), oxygen (O_2), and vibration data inside the nest was measured by means of the proposed developed system. As such, 27 samples were taken, and the results were then analysed to determine the characteristics based on these parameters. It should be noted that temperature, humidity, and pressure inside the nest were also measured and compared with the surface reference values.

4 Result & Analysis

This section discussed on the results and analysis, and it is divided into three subsections: Section 3.1, Section 3.2, and Section 3.3. Particularly, Section 3.1 presents the on-site surface environmental data, while Section 3.2 provides a comparison between the surface environmental with the nest data. Finally, Section 3.3 focuses on the specific atmosphere and structural vibrations from the sea turtle nest.

4.1 On-Site Surface Environmental Data (reference)

The measured temperature, humidity, and pressure at the surface are presented in Fig. 4, 5, and 6, respectively. These data were used as reference values for comparison with the measured parameters inside the nest. Based on Fig. 4, the average surface temperature was 31.59 °C. Meanwhile, the average humidity and pressure values at the surface were 67.91 %RH and 1010.53 hPa, respectively.

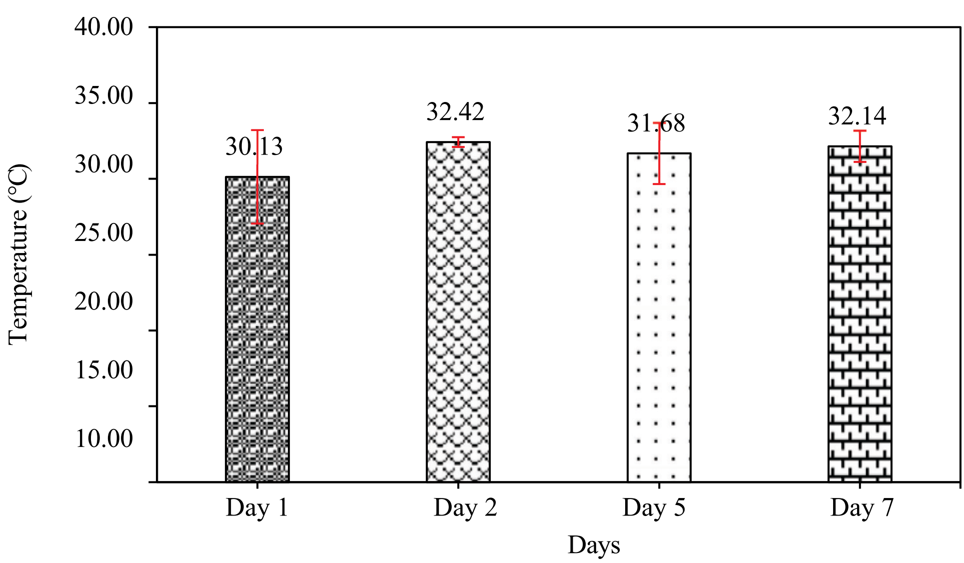

Fig. 4. Measured on-site surface temperatures.

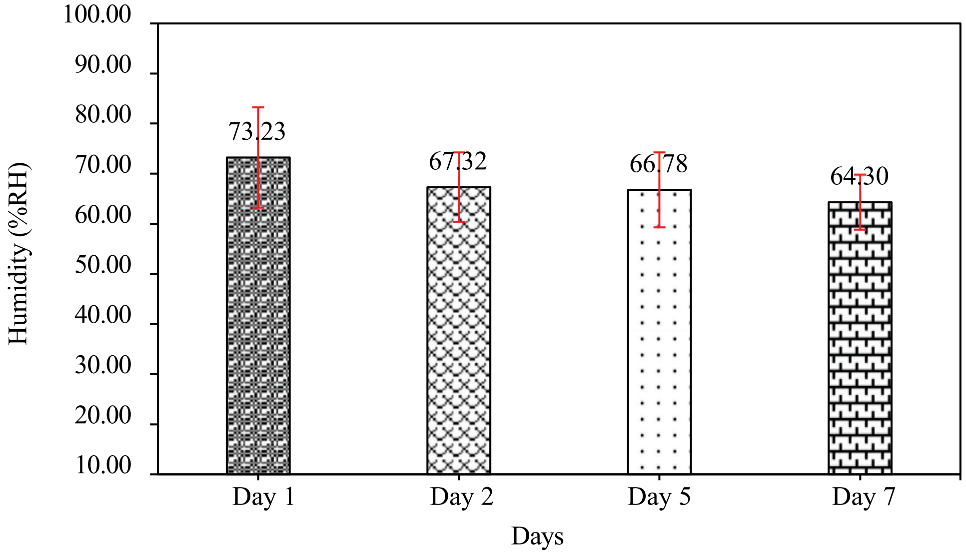

Fig. 5. Measured on-site surface humidity.

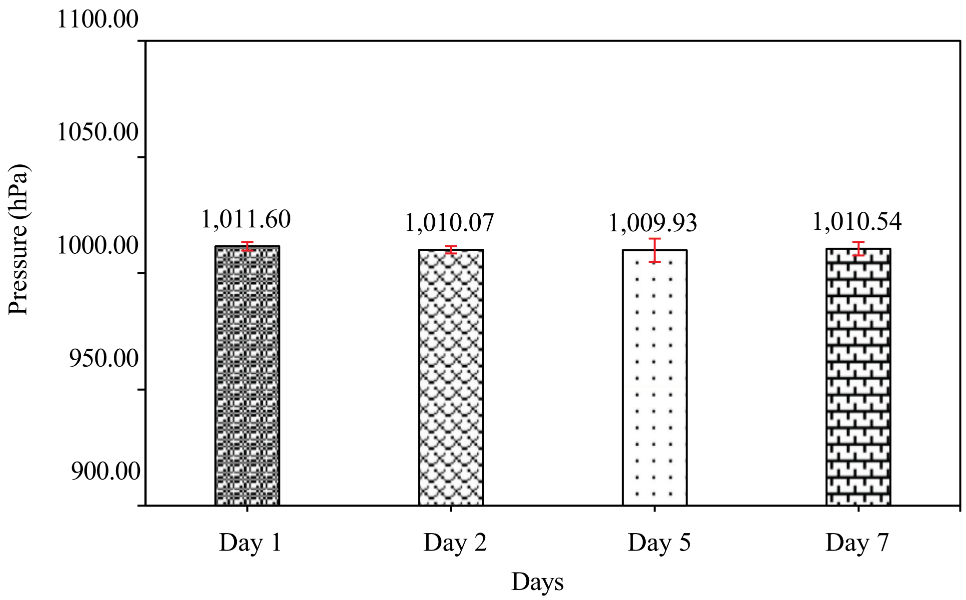

Fig. 6. Measured on-site surface pressure.

4.2 The environmental conditions comparing surface and nest

Fig. 7 and 8 illustrate the measured temperature and humidity levels inside the turtle nest compared to the reference surface conditions. The data show that both temperature and humidity are higher inside the nest than at the surface. Specifically, the average temperature inside the nest is 32.6 °C, while the average surface temperature is 31.3 °C. This represents a temperature difference of 1.3 °C, which is approximately a 4 percent increase.

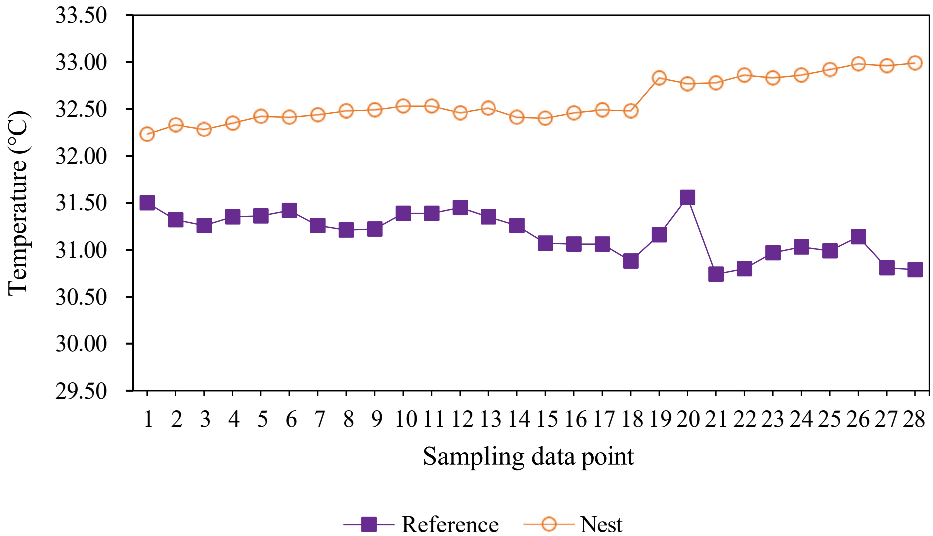

Fig. 7. Measured temperature comparing reference and nest.

In terms of humidity, the average surface humidity is 67 %RH, whereas inside the nest it is 81 %RH, an increase of 13 %RH or about 20%. These results suggest that the higher humidity levels inside the nest are due to moisture retained by the surrounding soil, which limits air circulation and creates a more stable microenvironment that supports embryonic development. The higher nest temperature can be attributed to the insulating properties of the sand, which reduces heat loss and buffer against surface temperature fluctuations. In addition to that, the deeper layers of sand retain heat more effectively, and the developing embryos generate metabolic heat, further raising the nest temperature. Moisture within the nest also contributes to heat retention by minimizing cooling through evaporation.

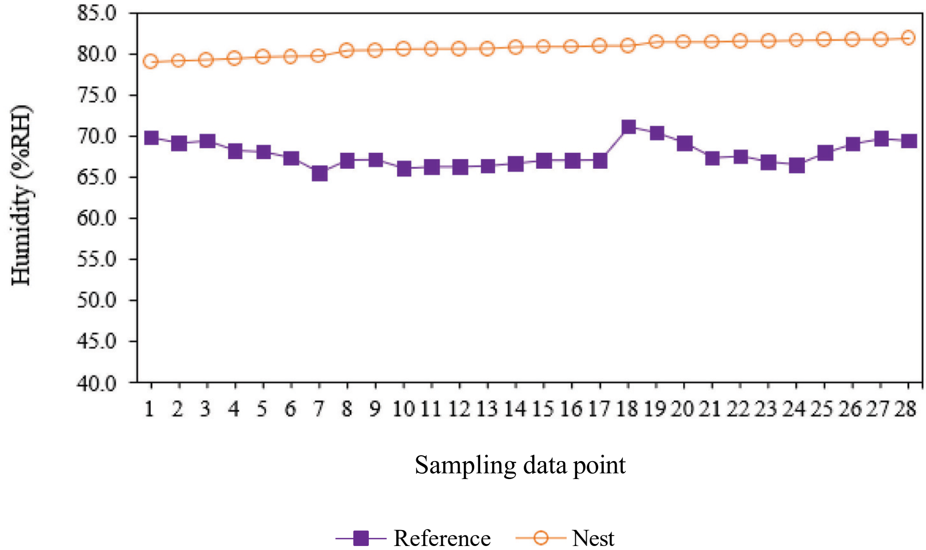

Fig. 8. Measured humidity comparing reference and nest.

4.3 Internal Nest Atmosphere and Structural Vibrations

The correlation between carbon dioxide (CO_2) levels and vibration inside the nest is shown in Fig. 9. Based on the results, carbon dioxide exhibits a proportional relationship with vibration, meaning that higher CO_2 levels correspond to increased vibration observed in the nest. While turtle eggs release carbon dioxide due to embryonic metabolism, this gas emission does not directly cause vibrations. This suggests that any vibrations detected are more likely caused by the physical movements of the embryos or hatchlings.

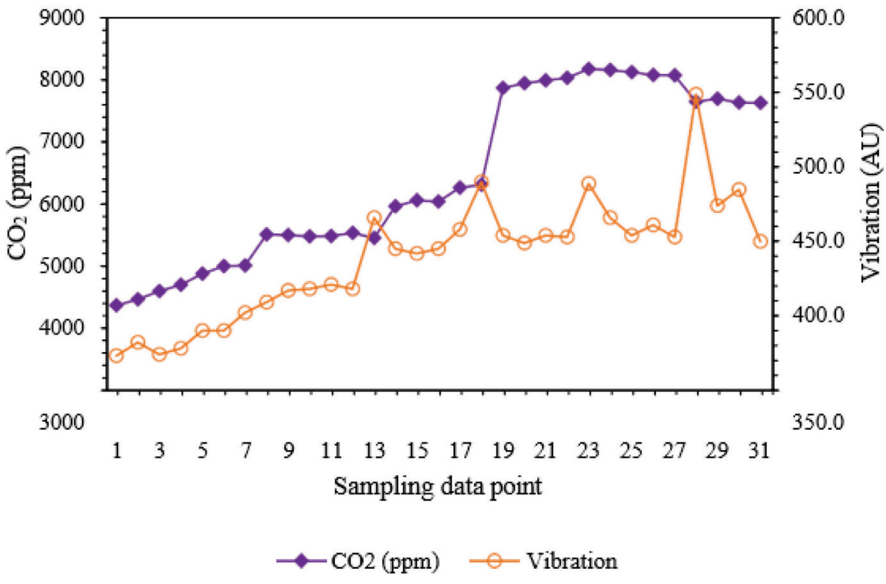

Fig. 9. The correlation of carbon dioxide levels and vibration inside the nest.

Fig. 10 reveals the correlation between vibration and the oxygen (O_2) levels inside nest. Significantly, O_2 and vibration exhibit an inverse relationship. Specifically, lower O_2 levels correspond to higher vibration activity. Consequently, as oxygen levels decrease, probably due to an increase in embryonic metabolism, the embryos become more physically active, causing the nest to vibrate more.

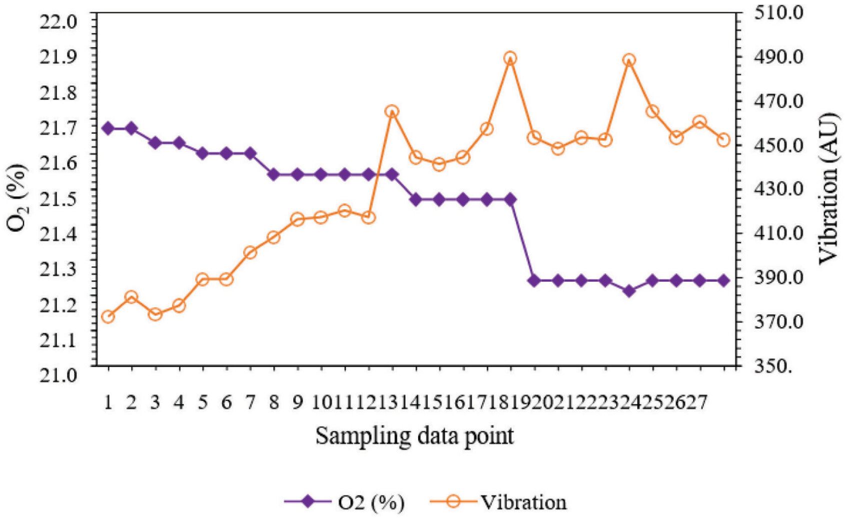

Fig. 10. The correlation of oxygen levels and vibration inside the nest.

Fig. 11 shows the correlation between CO_2 and oxygen O_2 levels inside the sea turtle nest. The results show that CO_2 and O_2 have an inverse relationship, where higher CO_2 levels correspond to lower O_2 levels. This suggests that within turtle eggs, O_2 levels decrease as the embryos consume it for metabolism, while CO_2 levels increase as a byproduct, resulting in an inverse relationship between the two gases.

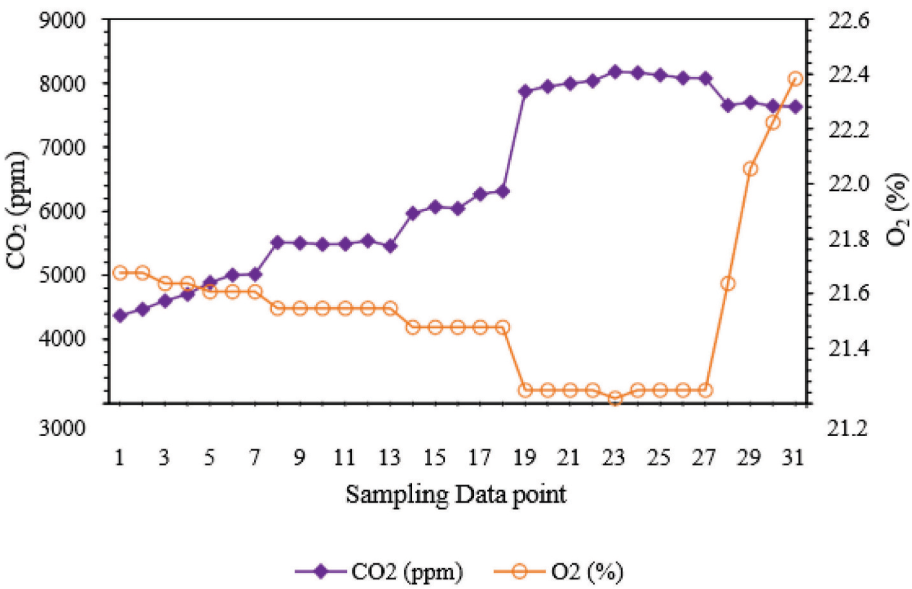

Fig. 11. The correlation of carbon dioxide levels and oxygen inside the nest.

5 Conclusion

The IoT-based real-time monitoring system for sea turtle nesting on Tengah Island, Mersing, Johor, has been successfully developed and validated. The findings indicate that the nest environment of turtles has higher temperature and humidity compared to the surface. Higher carbon dioxide concentrations, lower oxygen levels, and greater vibration activity were also observed within the nest. These patterns are driven by embryonic metabolism, limited air circulation, soil moisture retention, and the insulating properties of the surrounding sand. The developed IoT-based real-time monitoring system for sea turtle nesting effectively captured and provided environmental and physiological data. The platform not only enhances scientific understanding of sea turtle nesting conditions during the first week of incubation but also offers a practical and scalable solution for long-term monitoring in remote or off-grid conservation sites. This demonstrates its potential as a valuable tool for monitoring and supporting sea turtle conservation efforts.

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