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# Development of An IoT-LoRaWAN Sensor-Enabled Photobioreactor System for Characterizing the Growth of Microalgae

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**Abstract**

Microalgae cultivation is gaining attention in the food, pharmaceutical and biofuel sectors due to its potential to produce high-value products. However, relying on human interventions to monitor microalgae growth is labor-intensive and time-consuming. This study developed an Internet-of-Things (IoT) acquisition and monitoring system based on long-range wide area network (LoRaWAN) technology that integrates electrical conductivity (EC), oxidation-reduction potential (ORP), pH and temperature sensors to automate real-time microalgae growth monitoring. The data obtained from the sensors was sent to the InfluxDB cloud server for time-series database storage and visualized in the Grafana dashboard. The result of the study showed improvement in the efficiency and precision of monitoring, thus reducing reliance on manual data measurement. Incorporation of the system in microalgae cultivation also presents a source for continuous time series microalgae growth data. This approach will lead to strengthened automation in smart aquaculture and may provide a means to optimize microalgae productivity.

## 1. Introduction

The cultivation of microalgae is gaining wider recognition due to its capacity to produce value-added products for applications ranging from pharmaceuticals to food additives and biofuels [1, 2]. *Chlorella sp*. is known for its rapid growth rate, ability to absorb carbon dioxide [3, 4], high-value metabolites and antioxidant compounds [5]. The demand for microalgae-based fish feeds aligns with the growing global efforts to support the Sustainable Development Goals (SDGs), particularly in promoting responsible fishing practices and reducing the carbon footprint of the aquaculture sector. While the demand for renewable energy is unavoidable, there is also a shift towards alternative, sustainable fish feeds. Most aquatic animals need fishmeal as an essential ingredient [6]. However, limited supply and rising price of fishmeal are major constraints to its use in aquaculture [6]. As an alternative, protein- and fatty acid-rich microalgae like Chlorella sp. can accelerate fish growth rates [7], [8] in the aquaculture industry.

Various approaches for monitoring microalgae growth, integrating different sensing technologies for data acquisition and analysis, have been explored in several studies. For instance, the study from [9] integrates IoT to monitor spirulina biomass concentration. Similarly, [10] developed SABANA Data Services as an IoT cloud-based service for handling microalgae production data. The studies from [6, 7] highlights the importance of integrating automated monitoring systems in monitoring and optimizing microalgae farm production. Despite these benefits, effective monitoring of microalgae cultivation remains a challenge, particularly in ensuring real-time data acquisition for optimal growth conditions, which is labour-intensive, time-consuming, and less effective in providing accurate and real-time data [11]. Reliance on this conventional method is a significant obstacle to more efficient and automated control of culture environment conditions.

Several water quality parameters need to be monitored to understand the aquatic conditions [11] , especially in microalgae cultivation, including Oxidation-Reduction Potential (ORP) [12], Electrical Conductivity (EC) [13], pH and water temperature [14]. These parameters are crucial in determining the growth rate of microalgae and cell counts. Thus, there is a utility gap for monitoring and predicting algal growth [12, 13, 14]. Microalgae experience a series of growth phases: lag, exponential, stationary, and decline phases [15, 16]. Water quality parameters such as ORP, EC, pH, and thermal conditions are anticipated to significantly influence the algae culture's growth rate and overall stability within these developmental stages [20]. For instance, ORP is closely related to electron availability within the culture medium, thereby impacting the metabolic activities of microalgae [12]. EC indicates ion concentration within the medium, which correlates with the physiological health of algal cells. Optimal pH levels are essential for sustaining enzymatic activity within the culture [16, 17]. At the same time, temperature is a critical factor influencing both the photosynthesis rate and the microalgae's metabolic processes [19].

Long range wide area network (LoRaWAN) communication protocol is a media access control protocol (MAC) that stays at the physical layer's top level [21]. It allows long-distance data transmission with low energy consumption, making it suitable for IoT monitoring systems [15, 17] It provides stability and scalability while saving transmission time and energy on the end devices [22]. LoRaWAN supports data transmission rates ranging from 0.3 kbps to 50 kbps [23], making it suitable for real-time [24] sensor data transmission in IoT, machine-to-machine, and industrial applications [21, 22]. This low data rate provides several advantages, such as effective power consumption concerning battery life and Quality of Service (QoS) [26], latency, reliability, and transmission range [27]. Hence, the sensor monitoring system based on LoRaWAN can provide reliable and stable data transmission associated with the real-time [26] growth of microalgae. Therefore, the objective of this research is to develop an IoT-enabled multi-parameter water quality acquisition system for characterizing the growth of microalgae. This system will provide data, analyze, and improve the effectiveness of sensor data integration through IoT, enhancing the real-time monitoring of microalgae growth.

## 2. Methodology

The development of an IoT multiparameter data acquisition and monitoring system for microalgae cultivation consists of three layers (Figure 1): The physical Layer, in which sensors and end devices are attached in an indoor photobioreactor (PBR) cultured *Chlorella sp.*; the Network Server Layer, integration of IoT-LoRaWAN transmitting and managing sensor data; and the Application Layer, where data management, visualization, and analysis are done using cloud-based platforms in real-time.

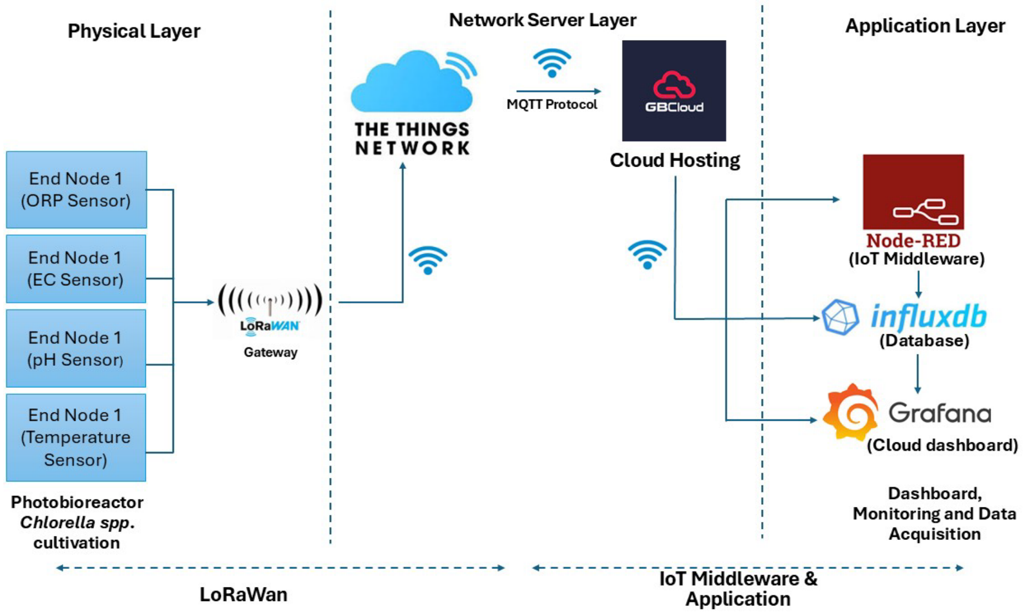


**Fig. 1** *Architectural diagram of the IoT-LoRaWAN multiparameter sensor data acquisition and monitoring system*

## 2.1 The Indoor Photobioreactor Microalgae Cultivation

The indoor photobioreactor cultivation was developed based on the parameters in Table 1, with a capacity of 4000 ml, inoculated with an initial density of 11.11 % wv$^{-1}$ (500ml) of *Chlorella sp*. The fertilizer used was organic, with a concentration of 1.25 % wv$^{-1}$ (50ml). The culture was maintained at 28°C with a white light illumination of 9.48 wm$^{2-1}$ at 0.5m for 16 hours daily. The sensors consist of a Gravity Analogue Industrial ORP sensor SEN0464, a Gravity Analogue Electrical Conductivity sensor PRO (K=1) SEN0451, a Gravity Analogue pH Sensor, and a DS18B20 Temperature sensor, which were placed in the microalgae culture, as shown in Figure 2. Prior to the continuous measurement, all sensors were calibrated using standard solutions: ORP (256 mV), EC (12880 uS/cm) and pH (buffer solution 4.01 @ 25 °C, 6.86 @ 25 °C, and 9.18 @ 25 °C). IoT data was collected at 10-minute intervals to ensure the accuracy and stability of the readings. To verify the IoT sensor readings, a SX731 portable pH/Conductivity/ORP/Temperature multiparameter meter was used to measure the water quality for comparison. The IoT data was cross-checked with a handheld SX731 probe by taking triplicate readings daily. Minor variations were observed because of sensor response and sensitivity differences. Additionally, images of the microalgae cells were captured using a Nikon TS-100 phase contrast microscope.

**Table 1** *Experimental parameters for indoor photobioreactor microalgae cultivation*

| Items | Parameters | Value |
|---|---|---|
| 1. | Microalgae inoculum concentration, type | 11.11% (500ml), *Chlorella sp.* |
| 2. | Medium volume (Filtered water) | 4000ml |
| 3. | Fertiliser inoculum concentration, type | *1.25% (50ml), Organic* |
| 4. | Light source | *LED fluorescent lamp* |
| 5. | Lighting period, intensity | *16 hours ( 8 hours resting period), 9.48 W/m$^2$* |
| 6. | Aeration | *24 hours, air pump* |

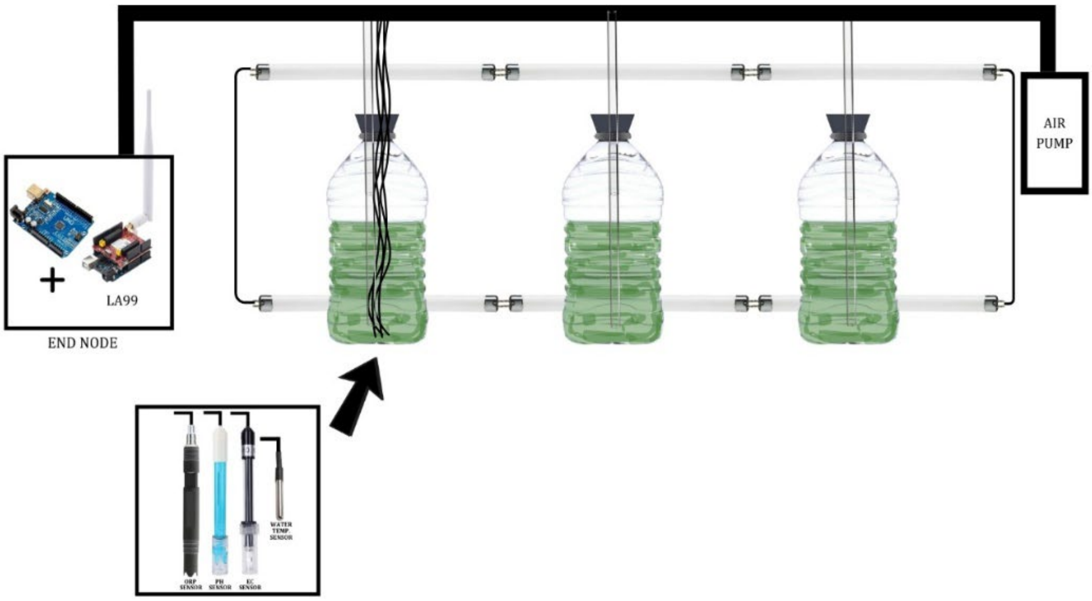


**Fig. 2** *Indoor photobioreactor medium setup under light exposure with inoculum concentration and fertiliser*

## 2.2 IoT-LoRaWAN Sensing System

Figure 3 shows the network server layer for integrating 4 sensors into the ATMega 328P 10-bit microcontroller and LA66 module. LA66 LoRaWAN shield provides a 915MHz transmission signal over 6 km of distance and supports LoRaWAN v1.0.3 protocol with low power consumption. LA66 data transmits the end node sensor data using the LoRaWAN protocol to the outdoor LoRaWAN gateway (DLOS8N, Dragino.com). Subsequently, the LoRaWAN gateway forwards the sensor data to The Things Network (TTN), the network server layer. DLOS8N sent data from the end node to the network server layer, The Things Network (TTN). From TTN, the data is used and connected to the IoT application layer, namely Node-Red, via the MQTT V3.1.1 protocol, as shown in Figure 4.

The application layer integrates with InfluxDB and Grafana to retrieve and display data acquired from sensors [25, 26] using the MQTT protocol [28]. Sensor data is stored and managed in InfluxDB, an open-source Time-Series Database [29] capable of handling large volumes of data [31]. This database provides users with an SQL-like query language, enabling operators to create interactive dashboards in real-time from the InfluxDB database [26, 27]. Through a configurable dashboard display, users can monitor changes in EC, ORP, pH, and temperature in real-time, enabling them to take faster corrective actions.

After the data are transmitted from sensors through the LoRaWAN communication protocol, they are processed by The Things Network (TTN) server and subsequently forwarded to the Node-RED application environment via the MQTT protocol. The data flow in Node-RED, which was developed to process, store, and visualize IoT sensor data in real time [29, 30, 31]. In Node-RED, all the data obtained from TTN is decoded into JSON format using the payload formatter and then visualized on the real-time monitoring dashboard.

The formatted data are then automatically stored in InfluxDB, a time-series database designed to receive and manage data measured at fixed intervals [34]. The use of InfluxDB ensures that all parameter changes are stored in chronological order, which is essential for this study. Subsequently, the stored data are visualized using Grafana, a dynamic time-series data visualization software [28, 32, 33]. Through Grafana, it is possible to interactively visualize daily and weekly trend patterns and identify any deviation in microalgae cultivation conditions.

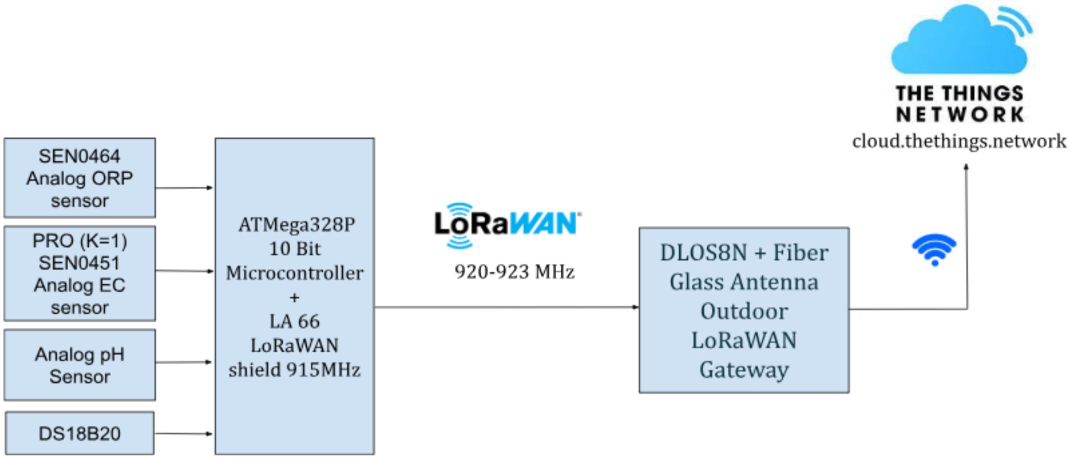


**Fig. 3** *System architecture of IoT-Based microalgae cultivation monitoring using LoRaWAN connectivity*

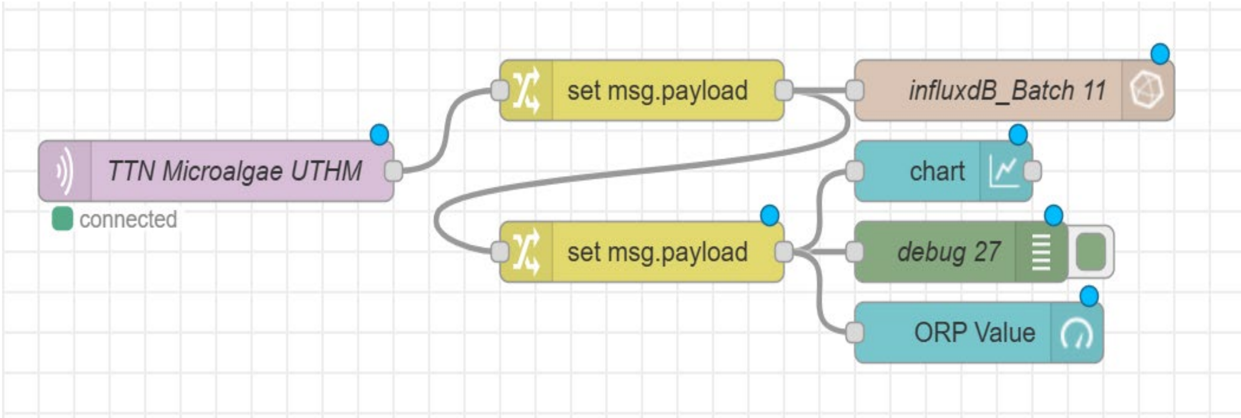


**Fig. 4** *Node-Red flow to Influx dB database via MQTT data acquisition*

## 3. Results and Discussion

The real-time integration of IoT technology with InfluxDB and Grafana via Node-RED enables the instantaneous visualization of measured data, such as ORP, EC, pH, and temperature, as shown in Figure 5. The displayed data presents the specific ORP, EC, pH, and temperature readings related to a microalgae cultivation experiment. Readings are displayed every 10 minutes, leaving a pattern trace that can capture and analyze multiple data points, providing a comprehensive view of the growth of the microalgae Chlorella sp. (Figure 5(a)-(d)).

Throughout the cultivation period, the ORP readings decreased gradually, which indicated active biochemical processes in the culture medium connected with photosynthetic activity by microalgae [13]. The EC level also showed a decreasing trend, corresponding to the nutrient absorption by microalgae cells during the growth process (Figure 5(b)). The pH level remained constant at a value near the optimal level (6.5-8.5), which created comfortable enzymatic activity conditions for microalgae metabolism. Meanwhile, the temperature was fairly stable, providing the cells with ideal growing conditions (27-29°C) (Figure 5(d)).

The recorded measurements of ORP, EC, pH, and temperature exhibit more distinct patterns of variation, which subsequently assist in rapidly plotting trends associated with microalgae growth and any potential environmental alterations. Time monitoring via IoT systems is more effective in understanding the dynamics of microalgae growth. In contrast, the manual sampling graph using SX731 portable handheld shows significant variations and less clear trends due to the limitations of periodic sampling and inconsistency, which may cause delays in identifying critical issues that could affect the health of the microalgae culture (Figure 5 (e)). The system's ability to automatically capture and store data every few minutes ensures that changes in the culture medium are accurately recorded.

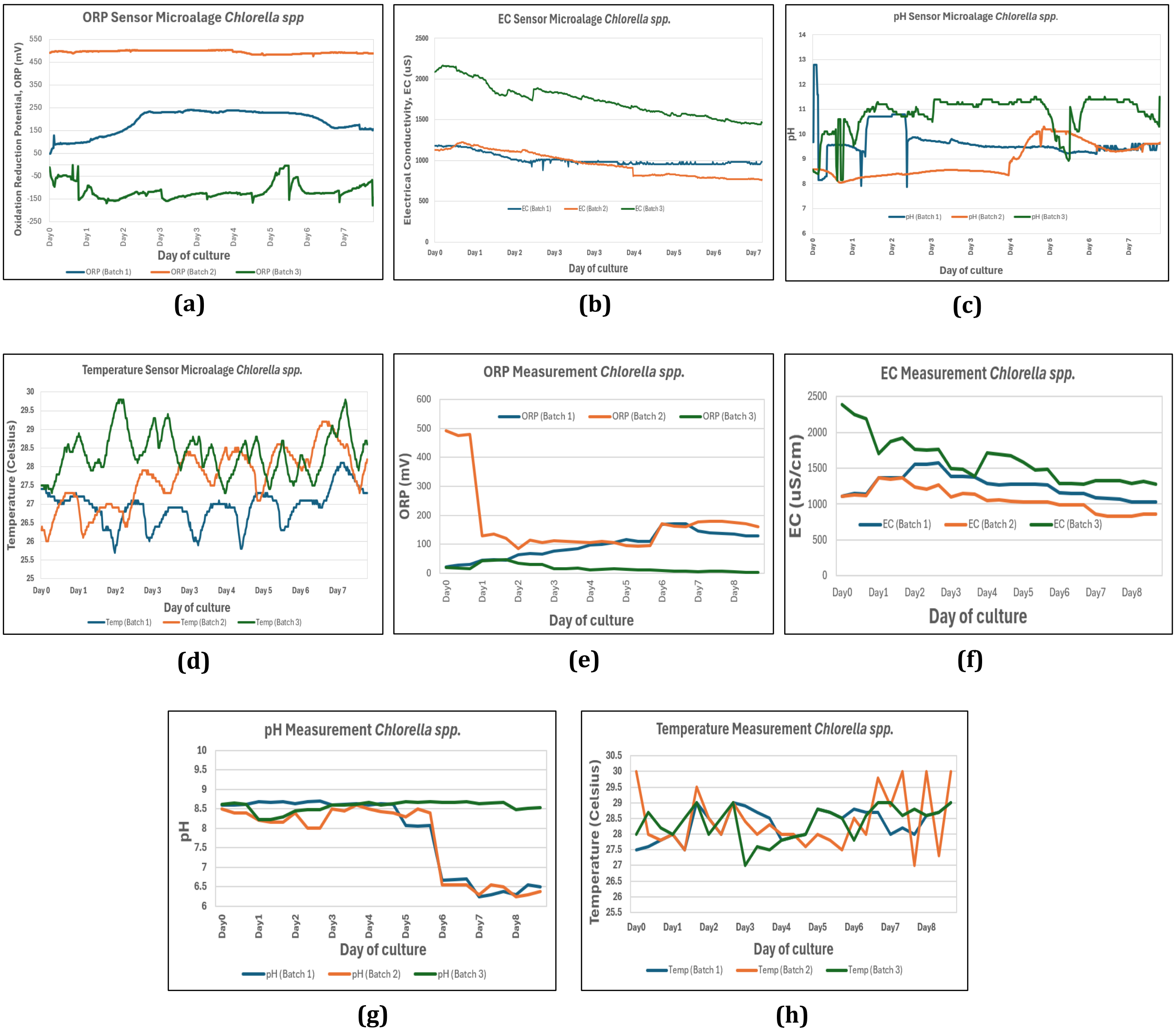


**Fig. 5** *Data acquisition of microalgae cultivation in three cycles: (a) ORP; (b) EC; (c) Ph; (d) Temperature, compared to SX731 Portable handheld measurement: (e) ORP; (f) EC; (g) pH; (h) Temperature*

As shown in Figure 6, the increase in microalgae cell proliferation (hemocytometer) is inversely correlated to the EC value. The EC value experienced a progressive decrease from 1170.5 µScm$^{-1}$ on day 2 to 768.3 µScm$^{-1}$ on day 8. This decrease indicates the continuous utilization of nutrient concentration by microalgae during growth, in line with the increase in total cell concentration from 132000 cellml$^{-1}$ on day 2 to 510000 cellml$^{-1}$ on day 8. These results indicate that microalgae *Chlorella sp*. experienced exponential growth when sufficient nutrient concentration was present in the initial stage [13]. However, as the nutrient source depletes, the growth is comparatively lower. This is due to conductivity in nutrient solutions, which is related to the number of ions present in the microalgae culture [8, 10]

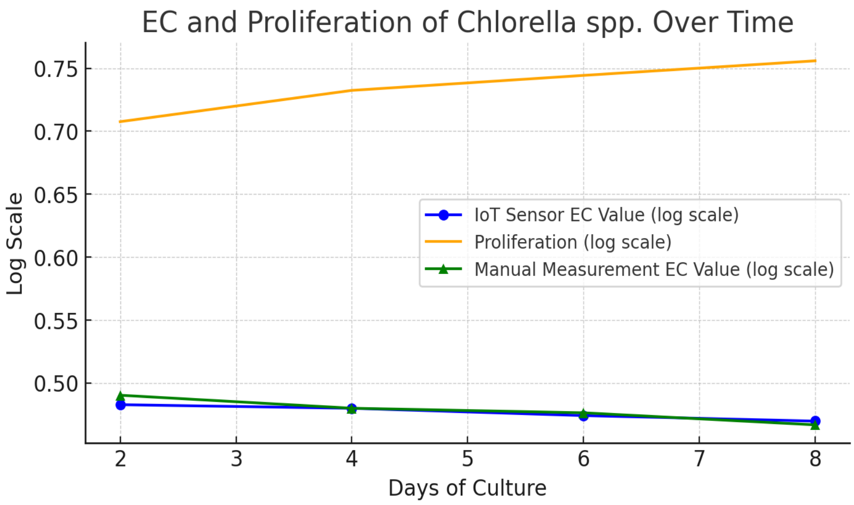


**Fig. 6** *Inverse correlation of EC values and proliferation rate over time*

The simultaneous decrease in EC value with the increase in microalgae cell proliferation illustrates the effectiveness of the IoT-LoRaWAN monitoring system in detecting changes in culture parameters in real-time. The findings present that the developed system has effectively improved the precision of microalgae growth monitoring. The readings obtained are real-time with continuous observations, reducing the variability rate from manual readings via SX731 (accuracy of EC reading is ±1.5% on the full scale and 0.01/0.1/1μS/cm resolution). The reduction in EC values and microalgae growth, as indicated in Figure 6, confirms the system's ability to effectively detect microalgae growth.

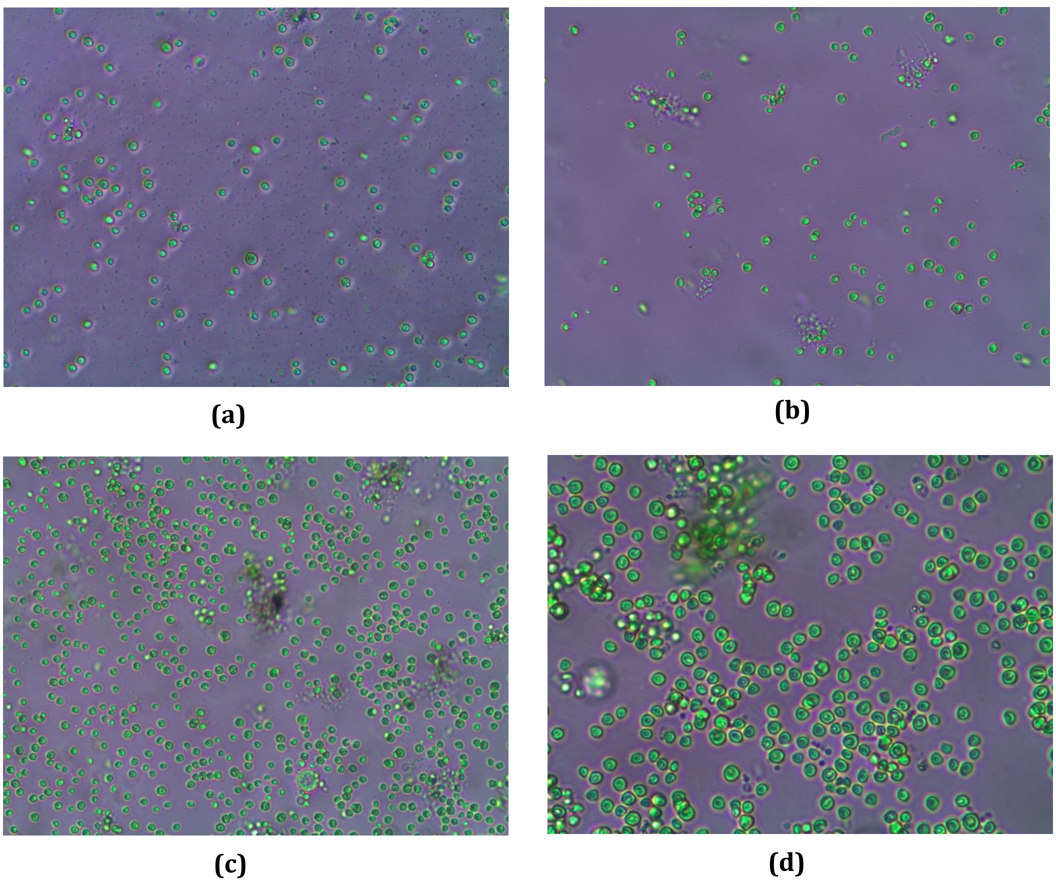


**Fig. 7** *Microscope images of Chlorella sp. cultivated: (a) Day 0; (b) Day 2; (c) Day 4; (d) Day 8*

The microscopic visuals in Figure 7 demonstrate the incremental increase in cell density within *Chlorella sp.,* throughout the cultivation timeframe, which aligns with the established growth trajectory of microalgae. At Day 0 (Figure 7(a)), the cell number is low, indicating the initial growth phase. By Day 2 (Figure 7(b)), the cells had started proliferating but were still in the adaptation phase. Day 4 (Figure 7(c)) reveals a significant increase in cell density, corresponding to an elevation in pH and ORP within the IoT framework, indicating more active metabolic activity. On Day 8 (Figure 7(d)), growth reaches its highest level, accompanied by a decrease in EC. These results indicate the microalgae growth curve from the lag phase until the decline phase [18]. The growth of microalgae biomass results in lower concentrations in the sample, indicating that the microalgae utilise the nutrients [13].

Figure 8 illustrates the alterations in the culture medium of the microalgae Chlorella sp. within the indoor photobioreactor across four distinct time points: Day 0, Day 2, Day 4, and Day 8. At Day 0, the culture medium looked clear with a low cell density, reflecting the lag phase in which the microalgae were adjusting to their new surroundings. On Day 2, the medium started to display a slight cloudiness, indicating the start of the adaptation phase and the early rise in metabolic activity. By Day 4, the changes in colour and turbidity of the medium became more evident, reflecting the rise in cell density noted through microscopic examination, along with the variations in ORP and pH values documented by the system. Ultimately, on Day 8, the culture medium exhibited the greatest turbidity, signifying the peak growth stage before transitioning into the nutrient depletion stage, a finding further corroborated by the reduction in EC values.


**(a)** **(b)** **(c)** **(d)**

**Fig. 8** *Results for indoor photobioreactor cultivation: (a) Day 0; (b) Day 2; (c) Day 4; (d) Day 8*

## 4. Conclusion

This study developed an integrated IoT-LoRaWAN monitoring system for real-time microalgae growth tracking, utilizing ORP, EC, pH, and temperature sensors for improved data accuracy and analysis. The combination of LoRaWAN, InfluxDB, and Grafana enabled stable data transmission, long-term data storage, and interactive visualization, thereby enhancing system functionality. Findings confirmed that the system improved monitoring efficiency, reduced reliance on manual methods, and enabled faster corrective actions. The fluctuations of water physical parameters, such as ORP, EC, and pH imbalances, were identified as key factors affecting microalgae growth. Overall, the system provided a scalable and efficient solution for smart microalgae farming. Its success paves the way for integrating digital twin and machine learning models, advancing predictive analytics and automation in smart aquaculture.

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## Conflict of Interest

The manuscript has not been published elsewhere and is not under consideration by any other journals. All authors have approved the review, agreed with its submission, and declared no conflict of interest in the manuscript.

## Author Contribution

*Mahdzir Jamiaan:* ***author, conceptualization, methodology, software, writing-original draft preparation and editing***; *C.F. Soon:* ***supervision, author, conceptualization, validation, writing-reviewing and editing***; *K.S. Chia:* ***writing-reviewing, validation and advisor***; *K.S. Tee, Norshuhaila Mohamed Sunar and Siti Nor Hidayah Arifin:* ***validation and advisor***; *Chris Heng*: ***advisor***.

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