VIETNAM GENERAL CONFEDERATION OF LABOUR
TON DUC THANG UNIVERSITY
FACULTY OF ELECTRICAL AND ELECTRONIC

DOAN DUY DUC

SMART IOT SYSTEM DESIGN FOR ALGAE FARMING – BLUE CARBON SOLUTION

UNDERGRADUATE THESIS OF AUTOMATION AND CONTROL ENGINEERING

HO CHI MINH CITY, YEAR 2025

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Instructor
ThS. Thieu Quang Tri

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ACKNOWLEDGMENT

I would like to express my sincere gratitude to ThS. Thieu Quang T, for the valuable knowledge he has imparted to me throughout the time I have had the privilege of studying under his guidance.

He has always brought new, engaging, and captivating knowledge that is highly suitable for my level. Thanks to his thoughtful preparation, we had the opportunity to receive and develop our understanding in the best possible way. It is based on the knowledge he has shared with us that I was able to complete my graduation project. The essential skills I have gained as a technical student will also support my personal growth and continuous development in the future.

Once again, I would like to sincerely thank Mr. Thieu Quang Tri, M.Sc., for the helpful knowledge he has conveyed during my learning journey under his mentorship.

Ho Chi Minh city, July 7, 2025

Author

This thesis was carried out at Ton Duc Thang University.
Advisor: Mr.Thiều Quang Trí,M.Sc

This thesis is defended at the Undergraduate Thesis Examination Committee was hold at Ton Duc Thang University on … /…/……

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Ho Chi Minh city, July 7, 2025

Author

Doan Duy Duc

(Trang này dùng để đính kèm Nhiệm vụ Đồ án tốt nghiệp có chữ ký của Giảng viên hướng dẫn)

TRƯỜNG ĐẠI HỌC TÔN ĐỨC THẮNG
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Độc lập – Tự do – Hạnh phúc

LỊCH TRÌNH LÀM ĐỒ ÁN TỐT NGHIỆP

Họ tên sinh viên: Đoàn Duy Đức
Lớp: 21H40301..MSSV: 421H0060
Tên đề tài: Thiết kế hệ thống IoT thông minh cho nuôi trồng tảo – Giải pháp Blue Cacbon

Tuần/Ngày	**Khối lượng**		**GVHD ký**
	Đã thực hiện	**Tiếp tục thực hiện**	
Tuần 1 (24/03-30/3/2025)	Nhận đề tài đồ án tốt nghiệp.	Tìm hiểu và nghiên cứu về đề tài.	
Tuần 2 (31/3-06/04/2025)	Tìm hiểu và nghiên cứu về đề tài.	Tìm hiểu quy trình nuôi tảo.	
Tuần 3 (07/04-13/04/2025)	Tìm nguồn cung con giống và chất dinh dưỡng .	Nghiên cứu, tính toán và lên thiết kế hệ thống.	
Tuần 4 (14/04-20/04/2025)	Tìm hiểu quy trình nuôi tảo.	Nghiên cứu, tính toán và lên thiết kế hệ thống.	
Tuần 5 (21/04-27/04/2025)	Nghiên cứu, tính toán và lên thiết kế hệ thống.	Tìm hiểu các loại cảm biến phù hợp.	
Tuần 6 (28/04-04/05/2025)	Tìm hiểu các loại cảm biến phù hợp.	Lựa chọn, thiết kế mô hình nuôi phù hợp.	
Tuần 7 (05/05-11/05/2025)	Lựa chọn, thiết kế mô hình nuôi phù hợp.	Lập sơ đồ khối và lưu đồ giải thuật, lập trình	
Kiểm tra giữa kỳ	Đánh giá khối lượng hoàn thành……..% được tiếp tục/không tiếp tục thực hiện ĐATN		

Tuần 8 (19/05-25/05/2025)	Lập sơ đồ khối và lưu đồ giải thuật, lập trình	Thiết kế board mạch.	
Tuần 9 (26/05-01/06/2025)	Thiết kế board mạch.	Thiết kế board mạch.	
Tuần 10 (02/06 - 08/06/2025)	Thiết kế board mạch.	Chạy thử nghiệm hệ thống	
Tuần 11 (09/06 -15/06/2025)	Chạy thử nghiệm hệ thống	Chạy thử nghiệm hệ thống	
Tuần 12 (16/06 -22/06/2025)	Chạy thử nghiệm hệ thống	Phân tích, đánh giá kết quả thu được.	
Tuần 13 (23/06 -29/06/2025)	Phân tích, đánh giá kết quả thu được.	Viết báo cáo	
Tuần 14 (30/06 - 06/07/2025)	Viết báo cáo	Viết báo cáo.	
Nộp Đồ án tốt nghiệp	Đã hoàn thành……..% Đồ án tốt nghiệp được bảo vệ/không được bảo vệ ĐATN		

THIẾT KẾ HỆ THỐNG IOT THÔNG MINH CHO NUÔI TRỒNG TẢO – GIẢI PHÁP BLUE CARBON

TÓM TẮT

Trong bối cảnh biến đổi khí hậu và ô nhiễm môi trường ngày càng nghiêm trọng, tảo đang được xem là một giải pháp sinh học tiềm năng giúp hấp thụ CO_2 và đóng góp vào quá trình giảm phát thải khí nhà kính. Từ định hướng đó, đề tài được xây dựng nhằm hỗ trợ việc theo dõi và quản lý quá trình nuôi trồng tảo một cách hiệu quả, tự động và tối ưu hơn.

Hệ thống được thiết kế tích hợp các cảm biến môi trường như cảm biến đo chất rắn hòa tan (TDS), cảm biến nhiệt độ, cảm biến pH và cảm biến oxy hòa tan (DO) nhằm thu thập các thông số quan trọng ảnh hưởng trực tiếp đến sự phát triển của tảo. Dữ liệu từ các cảm biến này sẽ được thu thập và truyền về vi điều khiển trung tâm (bằng ESP32 và Raspberry Pi), sau đó lưu trữ vào cơ sở dữ liệu để phục vụ phân tích và điều khiển.

Đặc biệt, hệ thống còn ứng dụng công nghệ xử lý hình ảnh thông minh từ camera và mô hình học sâu (Deep Learning) để nhận diện và phân tích mật độ tảo trong bể nuôi theo thời gian thực. Từ đó, hệ thống có thể phát hiện các dấu hiệu bất giúp người vận hành đưa ra các quyết định chính xác và kịp thời.

Kết quả của đề tài hứa hẹn sẽ góp phần vào việc hiện đại hóa hoạt động nuôi tảo theo hướng thông minh và bền vững, đồng thời đóng góp vào chiến lược phát triển kinh tế xanh – giảm phát thải carbon thông qua giải pháp Blue Carbon.

SMART IOT SYSTEM DESIGN FOR ALGAE FARMING – BLUE CARBON SOLUTION

ABSTRACT

In the context of increasingly severe climate change and environmental pollution, algae are being regarded as a promising biological solution for absorbing CO_2 and contributing to the reduction of greenhouse gas emissions. From that orientation, this project is developed to support the monitoring and management of algae cultivation in a more efficient, automated, and optimized manner.

The system is designed to integrate environmental sensors such as Total Dissolved Solids (TDS) sensor, temperature sensor, pH sensor, and Dissolved Oxygen (DO) sensor to collect key parameters directly affecting algae growth. Data from these sensors is gathered and transmitted to a central microcontroller (using ESP32 and Raspberry Pi), then stored in a database for analysis and control purposes.

Notably, the system also applies intelligent image processing technology using cameras and deep learning models to detect and analyze algae density in real-time. This enables the system to identify abnormal signs, helping operators make timely and accurate decisions.

The results of this project are expected to contribute to the modernization of algae farming in a smart and sustainable direction, while also supporting the green economic development strategy by reducing carbon emissions through the Blue Carbon solution.

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
AWS	Amazon Web Services
BDT	Broadband Digital Terminal
CO_2	Carbon Dioxide
CPU	Central Processing Unit
DO	Dissolved Oxygen
GPIO	General Purpose Input/Output
HDMI	High-Definition Multimedia Interface
HTML	HyperText Markup Language
IoT	Internet of Things
IP65	Ingress Protection Rating 65
LAN	Local Area Network
LED	Light Emitting Diode
ML	Machine Learning
PDF	Portable Document Format
PLA	Polylactic Acid
RAM	Random Access Memory
RS485	Recommended Standard 485
TDS	Total Dissolved Solids
USB	Universal Serial Bus
YOLO	You Only Look Once

CHAPTER 1. OVERVIEW OF THE PROJEC

1.1 INTRODUCTION TO THE PROJECT

In the context of climate change and environmental pollution becoming increasingly pressing global challenges, environmentally friendly biological solutions are receiving growing attention. Among these, algae are considered highly promising organisms due to their ability to rapidly and efficiently absorb CO_2, as well as their strong adaptability to various environmental conditions. Algae cultivation not only contributes to environmental remediation but also offers high economic value through applications in biofuel production, functional foods, pharmaceuticals, and industrial raw materials.

However, achieving high efficiency in algae cultivation requires close monitoring and flexible adjustment of environmental parameters such as temperature, pH level, dissolved oxygen concentration, and total dissolved solids in the water. The integration of Internet of Things (IoT) technology into agriculture—specifically algae farming—has become an inevitable trend to enhance automation, reduce labor costs, and improve production efficiency.

In response to this need, the project entitled "Design of a Smart IoT System for Algae Cultivation – A Blue Carbon Solution" was developed with the aim of establishing a real-time monitoring and management system for algae ponds. The system is equipped with sensors for total dissolved solids (TDS), temperature, pH, and dissolved oxygen (DO), enabling the collection of key environmental parameters. These data are processed by ESP32 and Raspberry Pi microcontrollers, stored in a database, and used for analysis, alerting, or automatic environmental adjustments when necessary.

A notable feature of the system is the integration of camera-based image processing and deep learning models to intelligently analyze the surface of the algae culture environment. This allows for the real-time detection of abnormal conditions such as algal blooms or biomass reduction, providing timely and effective support for operational decision-making.

This project not only delivers technical and technological value but also embodies a vision for sustainable development, greener production, and active contribution to greenhouse gas mitigation strategies. The Blue Carbon approach targeted by the system aligns with green economy initiatives by leveraging aquatic plant biomass to absorb and store carbon, thus simultaneously generating environmental and economic value.

1.2 RESEARCH OBJECTIVES

The primary objective of this study is to develop an intelligent monitoring and management system that applies Internet of Things (IoT) technology and artificial intelligence (AI) to algae cultivation, aiming to enhance production efficiency while promoting sustainable development and environmental protection.

Currently, algae farming not only generates economic value in sectors such as functional foods, pharmaceuticals, and biofuels, but is also recognized as an effective solution for carbon sequestration. It forms part of the Blue Carbon model, which involves using aquatic biomass to store and reduce greenhouse gas emissions, particularly CO_2. However, traditional algae cultivation methods face several limitations, including reliance on human experience, lack of continuous environmental monitoring, and difficulty in detecting abnormal water conditions in a timely manner.

Based on these challenges, this project defines the following specific research objectives:

- To design and implement an IoT-based system that integrates environmental sensors—including temperature, pH, dissolved oxygen (DO), and total dissolved solids (TDS)—to collect real-time data from the algae cultivation environment. This system enables continuous monitoring of key parameters directly affecting algae growth.

- To build a centralized database and data storage platform that allows users to remotely monitor, retrieve, and analyze collected data via microcontrollers (ESP32 or Raspberry Pi) connected to a Wi-Fi or Internet network.
- To apply image processing and deep learning models to analyze surface images of the algae tanks captured by cameras. The goal is to assess algae density in real time, enabling early detection of abnormal phenomena such as algal blooms, biomass reduction, or unusual discoloration—thus supporting timely and effective decision-making.
- To optimize cultivation conditions and increase automation by combining sensor data with AI-based decision-making or automated alerts. This helps reduce operational costs and improve overall production efficiency.
- To contribute to green production and sustainable development goals by supporting greenhouse gas emission reduction through the Blue Carbon solution—utilizing algae biomass to absorb CO_2 naturally and efficiently.

This project aims to develop a highly applicable, scalable model that can be implemented in small- to medium-scale algae farming systems. It supports the modernization of agricultural and aquacultural practices towards a smart, sustainable, and environmentally friendly approach.

1.3 RESEARCH SUBJECTS

- **Algae cultivation water environment**: The key parameters that need to be monitored include temperature, pH level, dissolved oxygen (DO), total dissolved solids (TDS), and light intensity. The water environment should maintain a slightly alkaline condition (pH from 8.5 to 9.5), a stable temperature range of 30–35°C, dissolved oxygen ≥ 5 mg/L, TDS between 1000–3000 ppm, and sufficient light (2000–5000 lux) to ensure effective photosynthesis. These conditions directly influence the growth rate and biomass density of microalgae.

- **Microalgae studied – Spirulina**: The cyanobacterium Spirulina platensis was selected as the primary subject of this research due to its fast growth rate, ease of cultivation, high protein content (55–70%), and strong CO_2 absorption capacity (~1.8–2.0 kg CO_2 per kg of biomass). Additionally, Spirulina thrives in alkaline water environments and is well-suited for cultivation in open pond systems. Other microalgae species such as Chlorella and Scenedesmus also show potential for Blue Carbon applications but are not the main focus of this study.

Figure 1.1 Spirulina platensis

- **Environmental monitoring system:** This system includes sensors for measuring temperature (DS18B20), pH, dissolved oxygen (DO), and total dissolved solids (TDS), all connected to an ESP32 microcontroller for real-time data acquisition. The collected data are processed, stored, and visualized through a Raspberry Pi, which provides an online monitoring dashboard. The system enables remote monitoring and early detection of abnormal changes in the water environment.

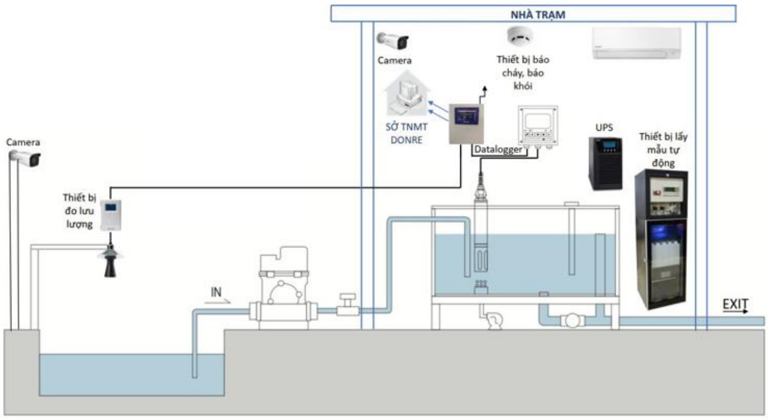


Figure 1.2 Block diagram of the environmental monitoring system

- **Application of artificial intelligence (AI):** Cameras integrated into the system (ESP32-CAM or webcam) capture images of the algae cultivation surface. These images are processed using deep learning algorithms (CNN, YOLO, or OpenCV) to analyze algae density and detect phenomena such as algal blooms, biomass reduction, or surface scum. AI supports early warning and timely decision-making.

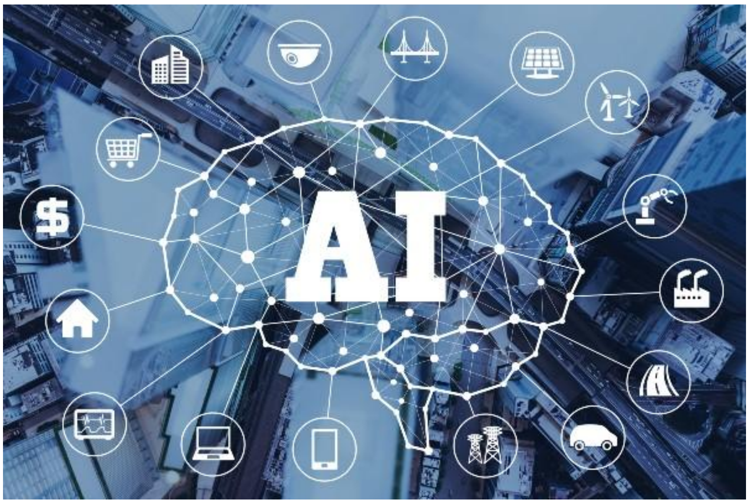


Figure 1.3 Ứng dụng của AI trong cuộc sống

- **Supporting devices and technologies:** The system utilizes ESP32, Raspberry Pi 4, Wi-Fi modules, power supply circuits, supplemental LED lighting, data transmission protocols (MQTT or HTTP), and databases (Firebase/MySQL). It is designed for continuous operation, low power consumption, and flexible scalability.

- **Economic and environmental factors**: The system helps reduce operational costs, save labor, and increase biomass production efficiency. Additionally, algae cultivation contributes to CO_2 absorption and the generation of valuable biomass, helping reduce greenhouse gas emissions and promoting the Blue Carbon model and circular economy toward sustainable development.

1.4 RESEARCH SCOPE

- **Spatial scope:**

The project is conducted on a laboratory scale or within a small-scale cultivation model in a confined area (less than 10 m^2), using plastic tanks or glass-framed containers with a water volume ranging from 50 to 200 liters for cultivating Spirulina. The experimental setup and system testing are carried out under semi-outdoor conditions or with artificial lighting to ensure environmental control.

- **Technical scope:**

The system is designed based on a basic IoT architecture, utilizing environmental sensors (temperature, pH, DO, TDS), an ESP32 microcontroller, a Raspberry Pi embedded computer, and a monitoring camera. The management software operates using Wi-Fi and MQTT protocols, with data storage on platforms such as Firebase or MySQL. The AI-based image processing model is applied solely to the analysis of algae density through still images or periodic snapshots, and does not yet support continuous real-time video processing.

- **Disciplinary scope:**

The research primarily focuses on monitoring and evaluating environmental conditions that influence the growth of Spirulina, incorporating sensor signal processing, AI-based image analysis, and the development of a data visualization dashboard. Biological aspects such as algae strains, cultivation procedures, and biochemical analysis of biomass are not the main focus of the study and are only referenced as supporting information for system design purposes.

- **Application scope:**

The system is developed and tested on a small scale, primarily for simulation purposes and to demonstrate the core principles. It is not yet intended for large-scale deployment or commercialization. However, the model holds potential for future expansion into industrial algae cultivation systems, particularly for small- to medium-scale algae farms involved in environmental treatment, CO_2 absorption, green biomass production, and contributions to a circular, green, and low-carbon economy.

1.5 EXPECTED OUTCOMES.

The project is expected to successfully develop an intelligent monitoring system for Spirulina algae cultivation, integrating IoT technology with artificial intelligence-based image processing. The system will be capable of collecting, transmitting, and storing real-time water quality data from sensors measuring temperature, pH, dissolved oxygen (DO), and total dissolved solids (TDS). Simultaneously, it will use a camera and AI models to analyze algae density and provide early warnings of abnormalities during the cultivation process.

The anticipated outcome is a stable, low-cost, and scalable model that can be applied in small-scale or pre-production scenarios. In addition, the system will generate valuable input data for evaluating the CO_2 absorption efficiency of algae, thereby contributing to the quantification of Blue Carbon potential within sustainable agri-biological models.

Through this approach, the project aims not only to support the technical aspects of algae cultivation but also to promote the development of smart agriculture, contributing to future carbon reduction strategies and the advancement of a green economy..

CHAPTER 2. RELATED STUDIES AND THEORETICAL FRAMEWORK

2.1 RELATED STUDIES

In recent years, the application of Internet of Things (IoT) and Artificial Intelligence (AI) technologies in aquaculture—particularly in microalgae cultivation—has gained increasing research interest. One notable study by S. Vasisht et al. (2019), titled "IoT-Based Monitoring System for Algae Cultivation", proposed a system utilizing Arduino to measure pH and temperature, transmitting data via Wi-Fi and displaying it on a basic user interface. However, the system lacked image processing capabilities, long-term data storage, and intelligent analysis integration.

In Vietnam, Nguyễn Văn Lợi and colleagues (2020) at Ho Chi Minh City University of Technology developed a system titled "Design of a Monitoring System for pH and Temperature in Spirulina Cultivation". Their system enabled real-time monitoring and displayed data on an internal website. Despite its practical relevance, it remained manually operated and lacked features such as image analysis or early warning mechanisms.

Focusing on image processing, Y. Kose et al. (2021) conducted a study called "AI-Powered Algae Detection Using Convolutional Neural Network", which employed CNN models to classify algae types from microscopic images. While this research provided valuable insights into microalgal image analysis, it was not integrated into an environmental monitoring or cultivation control system. Moreover, the use of microscopic imaging is impractical for outdoor or production-scale applications.

Commercial efforts also exist, such as AlgaeConnect (USA, 2022), which developed IoT-based algae monitoring systems with remote control platforms. However, these solutions are typically high-cost, proprietary, lack open-source flexibility, and do not incorporate AI-based image processing at the edge device level.

From these studies, it is evident that most current systems focus on isolated aspects—either environmental sensing, image processing, or remote control—rather than providing a fully integrated solution that combines all three: IoT, AI-based image analysis, and intelligent control. Additionally, few studies have addressed the role of microalgae in CO_2 absorption and the quantification of biomass for Blue Carbon strategies.

Therefore, this project aims to develop a comprehensive smart system that integrates environmental monitoring, algae density analysis, and anomaly detection. The goal is to contribute to a more efficient, sustainable, and modern model for algae cultivation, aligned with green economic development and carbon reduction strategies.

2.2 THEORETICAL FRAMEWORK

2.2.1 Theoretical framework of monitoring systems

The environmental monitoring system in Spirulina cultivation plays a crucial role in continuously collecting and tracking key parameters that directly affect the algae's growth process. The critical parameters include:

- pH level: Influences nutrient absorption and photosynthetic efficiency. Spirulina thrives in environments with a pH range of 8.0 to 11.0.
- Temperature: A determining factor for growth rate and productivity. The ideal temperature range is between 27°C and 30°C.
- TDS (Total Dissolved Solids): Indicates the concentration of dissolved nutrients in the culture medium. After each harvest, this value typically decreases, requiring monitoring for timely nutrient replenishment.
- DO (Dissolved Oxygen): Reflects the level of photosynthesis and overall health of the microalgal ecosystem. A sharp drop in DO may signal organic decomposition or biomass degradation.

To measure these parameters, the system utilizes specialized sensors:

- DO-S20 sensor: An integrated sensor capable of simultaneously measuring pH, DO, and temperature. It transmits data via RS485 protocol and features a corrosion-resistant casing suitable for aquatic environments.
- TDS sensor (DFRobot Gravity): Measures the concentration of dissolved solids and communicates through UART.

The ESP32 microcontroller serves as the central processing unit. It receives signals from the sensors, processes and displays the data through a user interface, and transmits it to a database for storage and further analysis..

a) DO S20 sensor

In the water quality monitoring system for algae cultivation, simultaneously measuring key parameters such as dissolved oxygen (DO), pH, and temperature is essential to maintain optimal growth conditions for microalgae. This study employs the integrated DO-S20 sensor, a multifunctional device capable of measuring all three parameters—DO, pH, and temperature—in parallel. The use of this sensor simplifies the hardware architecture, reduces overall system cost, and facilitates easier maintenance.

Figure 2.1 DO S20 sensor

The sensor operates based on an optical, electrode-free measurement principle for dissolved oxygen (DO), utilizing the phenomenon of fluorescence quenching to determine the DO concentration in water. When light from the emitter strikes the sensor spot containing fluorescent dye, the dissolved oxygen in the surrounding environment influences the fluorescence lifetime and intensity of the returned signal. The device measures these changes and accurately calculates the DO concentration without requiring direct electrode contact. This design eliminates issues such as corrosion, fouling, and the need for frequent calibration typically seen with electrochemical sensors.

For pH measurement, the sensor employs ion-selective electrode (ISE) technology to determine the acidity or alkalinity of the aquatic environment—a critical factor affecting algal biological activity and photosynthetic efficiency. Temperature sensing is also integrated to compensate for both DO and pH measurements, ensuring high accuracy under varying environmental conditions.

The DO-S20 sensor supports RS485 communication using the Modbus RTU protocol, making it well-suited for integration with embedded systems such as the ESP32 or Raspberry Pi. Sensor data is updated in real time and transmitted to a central processor for visualization via platforms like InfluxDB or Node-RED. With its high precision, durability, and ability to measure multiple parameters, the DO-S20 is an optimal solution for smart algae cultivation systems, enhancing operational efficiency and early warning capabilities.

b) TDS sensor

TDS (Total Dissolved Solids) is an index that measures the total concentration of dissolved substances in water, including minerals, salts, metals, and organic compounds—components that directly influence the purity and overall quality of the aquatic environment in algae cultivation tanks. During the cultivation process, the accumulation of nutrients, organic molecules, or impurities can alter TDS levels, thereby affecting nutrient absorption, photosynthesis efficiency, and the growth rate of the algae.

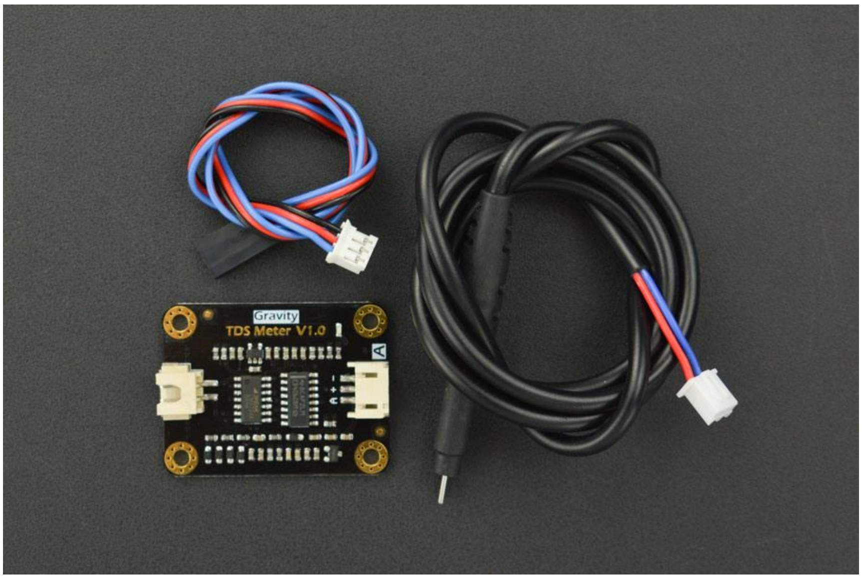


Figure 2.2 Gravity TDS Sensor

This project employs the Gravity TDS Sensor by DFRobot, a widely used device in IoT, hydroponics, and automated water quality systems. The sensor operates based on the principle of measuring the electrical conductivity (EC) of water: as the concentration of dissolved solids increases, so does the water's conductivity. From the measured EC value, the microcontroller (ESP32) calculates the TDS concentration in parts per million (ppm).

The sensor is designed with a non-polarized dual-electrode probe and supports a measurement range of 0–1000 ppm. It operates at 3.3V–5V and outputs an analog signal. An integrated signal amplifier and noise filter enhance measurement accuracy, especially in high-humidity environments or systems with electrical interference.

In the proposed system, the TDS sensor connects to the ESP32 via an analog-to-digital converter (ADC) pin. The data is processed on the microcontroller, transmitted to a storage system (InfluxDB), and visualized on a monitoring dashboard (Node-RED). This information is then used as the basis for adjusting nutrient concentrations as needed. The setup enables operators to assess and maintain optimal TDS levels for algae growth while also detecting abnormalities such as nutrient excess or deficiency in the cultivation tank.

2.2.2 Theoretical framework of nutrient supplementation systems

In algae cultivation systems particularly with Spirulina, a protein-rich microalga with high CO_2 absorption capacity it is essential to maintain an adequate supply of nutrients in the culture medium to support photosynthesis, biomass growth, and cell division. Proper nutrient supplementation is a key factor in achieving high productivity and maintaining ecosystem stability.

a) Essential nutrient components for algae

The necessary nutrients in algae cultivation environments are generally categorized into three main groups:

- Macronutrients:
  - Nitrogen (N): Essential for protein synthesis and chlorophyll production.
  - Phosphorus (P): Involved in cellular energy (ATP), DNA, and RNA.
  - Potassium (K): Regulates osmotic pressure and activates enzymes.
- Secondary nutrients:
  - Magnesium (Mg^{2+}): Structural component of chlorophyll.
  - Calcium (Ca^{2+}): Stabilizes cell membranes and supports metabolic processes.
  - Sulfur (S): Integral to amino acid and protein structure.
- Micronutrients:
  - Including: iron (Fe), zinc (Zn), manganese (Mn), copper (Cu), molybdenum (Mo), etc., which act as catalysts and play essential roles in enzymatic reactions and metabolic processes.

These nutrients are typically mixed according to standardized formulations and dissolved in water to create nutrient solutions for periodic supplementation in the algae cultivation tanks.

b) Operating principles of the supplementation system

The system employs sensors to monitor environmental parameters:

- pH and TDS sensors are directly installed in the cultivation tank to measure ion concentration and alkalinity.

- When these parameters fall below preset thresholds (e.g., low TDS or out-of-range pH), the ESP32 microcontroller triggers a mini electric pump to inject the pre-mixed nutrient solution.
- This process can operate in semi-automatic or fully automatic modes by implementing logical conditions through the Node-RED platform.

c) Role and benefits of an intelligent nutrient supplementation system

- Ensures stable algal growth and reduces biomass loss due to nutrient deficiency.
- Optimizes operational costs by enabling precise nutrient dosing and minimizing waste.
- Enhances photosynthetic efficiency, thereby improving CO_2 uptake performance.
- Reduces human error by leveraging real-time sensor monitoring and automation.

2.2.3 Theoretical background of AI and machine learning in environmental monitoring

a) Overview of artificial intelligence and machine learning

Artificial Intelligence (AI) is a field of research and development focused on creating systems capable of performing tasks that traditionally require human intelligence, such as reasoning, learning, analyzing, and decision-making. A key subfield of AI is Machine Learning (ML), which enables systems to learn from historical data in order to make predictions or classify new data.

Unlike traditional programming, ML does not require explicit instructions for every case. Instead, it uses mathematical models to discover patterns within data. The learning process typically consists of:

- Training: The model learns from input–output data pairs.
- Validation: The model's performance is evaluated for accuracy.
- Inference: The trained model is applied to new, unseen data for prediction.

b) Basic concepts and formulas

- Loss function: A metric used to quantify the error between the predicted output and the actual value. The objective in machine learning is to minimize this loss. A common example is the Mean Squared Error (MSE):

$$\mathcal{L} = \frac{1}{n}\sum_{i=0}^{n} (yi - \widehat{Y_\iota})^2$$

Where::

- Y_i: actual value
- $\widehat{Y_\iota}$: predicted value
- n: number of data points

- The ReLU function (short for Rectified Linear Unit) is one of the most widely used nonlinear activation functions in modern deep learning models, especially in Convolutional Neural Networks (CNNs).
It is defined by the formula:

$$f(x) = \begin{cases} 0, if\ x < 0 \\ x, if\ x \geq 0 \end{cases} or:\ f(x) = max(0, x)$$

=> ReLU functions as an information filter, enabling the network to learn meaningful features by zeroing out irrelevant (negative) values while retaining significant (positive) values through its linear activation.

- Softmax function (multi-class classification): typically used in the output layer to convert raw scores into probability distributions over multiple classes:

$$P(y_i = k) = \frac{e^{zk}}{\sum_{i=1}^{K} e^{Zj}}$$

Trong đó:

- $P(y_i = K)$: is the probability that data sample iii belongs to class k.
- Zk: is the unnormalized output (score or logit) of the model for class k.
- K: is the total number of target classes.

– $\sum_{i=1}^{K} e^{Zj}$: is the normalization term (the sum of all exponentiated scores), which ensures the output forms a valid probability distribution (i.e., the total sum is always ≥ 1).

c) Application in algae cultivation monitoring systems

In this study, machine learning is applied to two main task groups, integrating data collected from both the camera and environmental sensors:

- System fault detection

In the algae cultivation monitoring system, the ESP32-S3-WROOM-1U serves as the central microcontroller. It collects data from the TDS sensor (analog) and the DO-S20 sensor (via RS485 to UART), processes the signals, and compares the results against predefined threshold values. When necessary, the ESP32 controls actuators such as the aeration pump relay or the nutrient dosing pump. Simultaneously, data is transmitted to the Raspberry Pi 4 via the MQTT protocol, enabling the system to operate automatically and in real-time.

- Algae health prediction:

Beyond bubble detection, the system also analyzes images to identify changes in water color and surface clarity. These factors are critical indicators of biomass density, algae growth conditions, or signs of degradation such as nutrient deficiency or environmental imbalance. Based on the image analysis results, the system can suggest appropriate interventions, such as adding nutrients, adjusting light intensity, or increasing aeration duration, to stabilize growth conditions and optimize algae productivity.

By combining sensor data with visual analysis, the system enhances the accuracy of environmental assessment and supports automated decision-making..

2.3 MAIN COMPONENTS IN THE CONTROL CIRCUIT

2.3.1 ESP32-S3-WROOM-1U-1U

The ESP32-S3-WROOM-1U is a high-performance microcontroller module developed by Espressif Systems, built on the ESP32-S3 SoC. This module fully supports Wi-Fi 802.11 b/g/n and Bluetooth 5 (LE) wireless connectivity. It integrates AI acceleration capabilities through vector instructions and is uniquely designed without a built-in PCB antenna. Instead, it uses an external antenna via a u.FL connector, making it suitable for industrial environments that demand stable signal transmission or installation inside metal enclosures.

Figure 2.3 ESP32-S3-WROOM

- **Key technical specifications:**

– CPU: Dual-core Xtensa® LX7, 240 MHz

– RAM: 512 KB SRAM và PSRAM 8 MB

– Flash: 8 MB - SPI flash

– Operating voltage: 3.0 V – 5 V

– Wi-Fi: IEEE 802.11 b/g/n (2.4 GHz)

– Bluetooth® 5.0 LE with long-range và Mesh

– I/O: More than 40 pins GPIO, hỗ trợ UART, SPI, I2C, ADC (12-bit), DAC (8-bit), PWM

– AI acceleration support, TensorFlow Lite for Microcontrollers

– USB OTG communication (USB 1.1)

- **Programming environment:**
  - ESP-IDF (Espressif IoT Development Framework
  - Arduino IDE, PlatformIO
  - MicroPython

In the algae cultivation monitoring system, the ESP32-S3-WROOM-1U functions as the central microcontroller unit (MCU). It collects data from the TDS sensor (analog) and the DO-S20 sensor (via RS485 to UART), then processes the signals and compares them against predefined threshold values. When necessary, the ESP32 controls actuators such as air pump relays or nutrient dosing pumps. Simultaneously, all collected data are transmitted to a Raspberry Pi 4 via the MQTT protocol, enabling the system to operate automatically and in real time.

2.3.2 Raspberry Pi 4

The Raspberry Pi 4 is a single-board computer (SBC) developed by the Raspberry Pi Foundation, originally designed to support computer science education and digital literacy. However, due to its high performance, low cost, and flexible programmability, the Raspberry Pi 4 has become a widely adopted platform in various digital applications, particularly in embedded systems and Internet of Things (IoT) projects.

In terms of hardware, the Raspberry Pi 4 is powered by a Broadcom BCM2711 processor featuring a quad-core 64-bit ARM Cortex-A72 CPU clocked at 1.5 GHz, enabling efficient multitasking. It is available in RAM configurations of 2 GB, 4 GB, or 8 GB LPDDR4, and supports storage via microSD card or external hard drive through USB 3.0 ports. Key communication interfaces include Gigabit Ethernet, 802.11ac Wi-Fi, Bluetooth 5.0, and a 40-pin GPIO header that allows for peripheral expansion.

From a software perspective, the Raspberry Pi 4 runs on the open-source Raspberry Pi OS (based on Debian Linux), which supports a wide range of programming languages such as Python, C/C++, and Node.js. Additionally, the platform supports the deployment of server-side applications including Mosquitto (MQTT broker), InfluxDB (time-series database), and Node-RED (graphical dashboard interface) – all of which are key components in the modern IoT ecosystem..

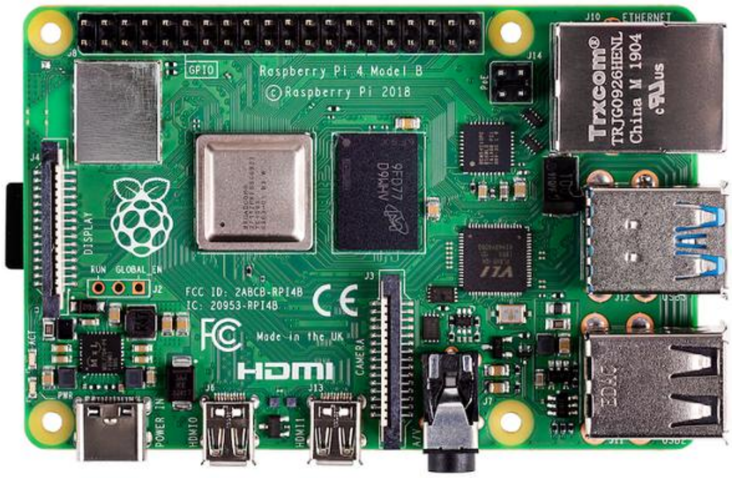


Figure 2.4 Raspberry Pi 4

In the algae farming monitoring system, Raspberry Pi 4 functions as a central local server, performing several critical tasks, including:

- Receiving data from the ESP32 microcontroller via the MQTT protocol, acting either as a subscriber or broker depending on the configuration.
- Storing sensor data (pH, temperature, DO, TDS) in an InfluxDB time-series database, ensuring data integrity and enabling real-time querying and visualization.
- Displaying data through the Node-RED Dashboard, allowing users to monitor environmental indicators via an intuitive web-based interface.
- Capturing periodic images from a USB camera to support image processing and algae health analysis using computer vision techniques.
- Supporting the training and deployment of machine learning (ML) models for system evaluation and autonomous control decision-making.

The integration of Raspberry Pi 4 enhances the system's modularity, simplifies hardware architecture, and increases scalability and customization capabilities—

making it well-suited for smart IoT applications in aquatic farming and environmental monitoring..

2.3.3 IC LM2596

The LM2596 is a buck-type DC-DC converter integrated circuit (IC), classified under high-efficiency switching regulators. It is widely used in electronic circuits that require stepping down a high input voltage to a lower, stable, and adjustable output voltage.
This IC operates with an input voltage range from 4V to 40V DC and provides an adjustable output voltage between 1.25V and 37V DC, capable of delivering a maximum load current of up to 2A. By employing switching techniques at a frequency of 150 kHz, the LM2596 achieves high efficiency, typically over 80%, significantly reducing energy losses compared to linear voltage regulators.

Figure 2.5 IC LM2596

The LM2596 is commonly integrated into modules that include an output adjustment potentiometer, filter capacitors, and a Schottky diode, which simplifies system integration. These modules are typically equipped with essential protection features such as:

- Overcurrent protection

- Overtemperature protection
- Output short-circuit protection

In the algae monitoring system, the LM2596 is used to step down the 12 V DC supply to 5 V DC, providing a stable voltage source for sensitive components such as the ESP32-S3 microcontroller, relay modules, TDS sensors, and other logic control circuits. Thanks to its ability to deliver a steady current, this IC ensures continuous and safe operation of the system, even under harsh environmental conditions..

2.3.4 RS485

RS485 (Recommended Standard 485) is an industrial serial communication standard designed for efficient and reliable data transmission in environments with high electromagnetic interference (EMI). It is widely adopted in monitoring and control systems, industrial automation, and protocols such as Modbus RTU, Profibus, and SCADA.

RS485 employs differential signaling using two signal lines, A and B, instead of absolute voltage levels as in conventional UART. This method enhances noise immunity and ensures data integrity over long distances.

- Key technical specifications:
  - Transmission type: Half-duplex, differential
  - Wiring configuration: Two main signal lines (A and B), with optional GND for synchronization
  - Maximum transmission distance: Up to 1200 meters at low speed (~100 kbps)
  - Maximum data rate: Up to 10 Mbps (at short distances ≤ 15 m)
  - Device capacity: Supports up to 32 transceivers on a single bus (expandable to 128+ with modern drivers)
- Logic levels:
  - Logic “1”: $V_A - V_B > +200$ mV
  - Logic “0”: $V_A - V_B < -200$ mV
- Advantages of RS485:

- Reliable long-distance data transmission with minimal signal degradation
- High noise immunity, ideal for EMI-intensive environments
- Supports multi-drop communication, reducing cabling complexity
- Simple and cost-effective to implement

In this project, the RS485 standard is employed to connect the DO-S20 sensor (which integrates DO, pH, and temperature measurements) to the ESP32-S3 microcontroller via a MAX485 transceiver module. This setup ensures stable and accurate data transmission, enabling continuous and reliable monitoring for the algae cultivation system.

2.4 SOFTWARE TOOLS FOR SYSTEM DESIGN

2.4.1 Autodesk Fusion 360 software

Autodesk Fusion 360 is a parametric 3D modeling software that integrates a comprehensive suite of tools, including mechanical design, simulation, CNC machining, rendering, and cloud-based collaboration. Developed by Autodesk, Fusion 360 is cross-platform, supporting both Windows and macOS, and allows users to synchronize data via the cloud, making it easy to access, share, and collaborate on design projects.

Thanks to its modern and intuitive interface and the integration of various design modules in a single environment, Fusion 360 is increasingly applied in fields such as precision engineering, electronic device manufacturing, prototype modeling, industrial design, and automated control system development.

Key features of Fusion 360:

- 3D design (Solid Modeling, Surface Modeling): Supports building detailed models from 2D sketches using tools such as Extrude, Revolve, Loft, and Sweep, with freeform shaping via Form tools.
- Assembly: Allows creation of assemblies from multiple components, checking joints, motion constraints, collisions, and mechanical fits.

- Technical drawing generation (Drawing): Automatically generates 2D drawings from 3D models with complete dimensions, tolerances, annotations, section views, and technical symbols compliant with standards.
- Simulation & FEA: Simulates stress, deformation, torque, thermal loading, and vibrations to evaluate structural integrity before actual manufacturing.
- CAM manufacturing (Manufacture): Includes an integrated CAM module for programming 2D/3D CNC machining directly from the 3D model—supports turning, milling, drilling, etc.
- Parametric design: Enables dimension constraints and interdependencies between components, allowing the model to update automatically when parameters change.
- Rendering & production file export: Supports exporting STEP, STL, IGES, DXF, DWG files, and realistic 3D rendering with material and lighting settings.

Figure 2.6 Autodesk Fusion 360 software

In this project, Fusion 360 is used to design the 3D model of the monitoring device enclosure and the protective case for the Raspberry Pi 4. This modeling process ensures that all components are accurately, neatly, and safely arranged during operation. The design includes features such as cable slots, screw holes, ventilation gaps, and removable covers for easy assembly. Once completed, the drawings are exported in DXF format for laser-cutting acrylic or in STL format for 3D printing.

2.4.2 Altium Designer software

Altium Designer is an integrated electronic design automation (EDA) software developed by Altium Limited. It is one of the most professional and powerful electronic circuit design tools currently available, widely used in research, product development, and industrial manufacturing.

Altium Designer allows the entire electronic circuit development process to be designed on a single platform from schematic capture, PCB layout design, circuit simulation, to fabrication drawing output and design rule checking (DRC).

With an intuitive interface, rich component libraries, and strong integration with simulation tools, Altium Designer effectively supports students, engineers, and enterprises in creating high-quality electronic products, ranging from consumer devices to industrial control systems, IoT devices, and medical equipment.

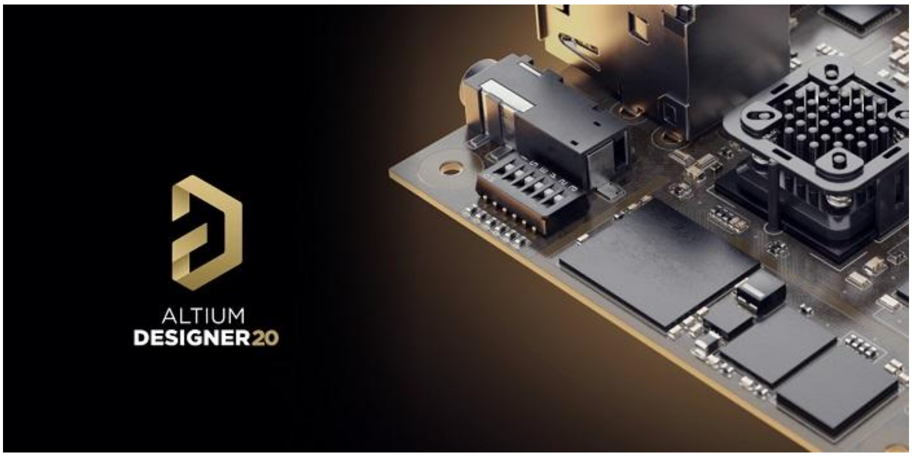


Figure 2.7 Altium Designer software

- Main features of Altium Designer:
  - Schematic capture: Supports intuitive logic circuit design and easy component linking.
  - PCB design: Creates layouts from single-layer to multi-layer boards, supporting both auto and manual routing.
  - Design rule checks (DRC/ERC): Detects connection errors and design rule violations before manufacturing.

- Component library management: Allows creation, management, and use of custom electronic components as needed.
- Circuit simulation: Supports digital and analog simulation to verify operation before production.
- Production file output (Gerber, BOM, etc.): Easily generates Gerber files, drill files, and bill of materials (BOM) for fabrication.
- 3D integration and mechanical checks: Displays 3D models of PCBs, checks dimensions, and verifies compatibility with enclosures or mechanical frames.

Altium Designer serves as the main software for electronic circuit design, supporting data acquisition from sensors, signal processing, power supply, and device communication within the algae farming system. Specific applications include:

- Designing the central control circuit with ESP32-S3: Using Altium to draw the schematic of the main control circuit based on the ESP32-S3 WROOM-32 microcontroller; laying out the PCB with I/O pins connected to sensors, UART, camera, and power.
- Designing industrial sensor interface circuit: Creating the RS485-TTL conversion circuit using the MAX485 IC, for reading data from the DO-S20 sensor (measuring DO, pH, temperature), ensuring stable, noise-resistant signals to ESP32.
- Designing the TDS sensor interface circuit: Designing the circuit to read signals from the Gravity TDS sensor via analog or UART, adding RC filters to remove noise before feeding signals to the microcontroller.
- Designing the power supply circuit for the whole system: Using LM2596 IC to provide stable 3.3V and 5V power for ESP32, sensors, and communication modules; including protection circuits against reverse polarity and overcurrent.

- Designing communication interface between ESP32 and Raspberry Pi 4: Drawing UART connection schematics for transmitting trigger signals from the microcontroller to the server for image processing and data storage.

2.4.3 Node-RED software.

Node-RED is an open-source software developed by IBM, designed for building Internet of Things (IoT) applications using a visual flow-based programming approach. Instead of writing complex code, users can simply drag and drop functional blocks (nodes) to create data processing flows, which helps save time and reduce system implementation complexity.

Node-RED is written in JavaScript (running on the Node.js platform), and it is highly compatible with multiple operating systems such as Windows, Linux, and Raspberry Pi. The software is especially well-suited for IoT systems that require communication with devices and sensors, as well as data processing and visualization..

Figure 2.8 Node-RED software.

Key features of Node-RED:

- User-friendly drag-and-drop programming: Allows users to build logic flows without requiring advanced coding skills. Nodes are linked together to form a clear and intuitive processing diagram.
- Versatile IoT communication: Supports various protocols such as MQTT, HTTP, Modbus, and TCP/IP, making it easy to interact with ESP32, Raspberry Pi, and industrial sensors.
- Database integration: Easily connects to databases like InfluxDB, MySQL, and Firebase for real-time data storage and historical data retrieval.
- Dashboard creation: Provides widgets like charts, gauges, and status indicators for users to monitor sensor values directly via web browsers.
- Automation and alerts: Enables creation of flows to send email alerts, control devices, or trigger actions when values exceed predefined thresholds.
- Strong community support: Thousands of additional nodes are available for integration with AI, device control, cloud services, messaging, and more.

In the proposed system, Node-RED serves as the central platform for orchestration and data visualization:

- Connects with ESP32 via MQTT or UART to receive data from sensors such as pH, temperature, TDS, and DO.
- Writes sensor data to the InfluxDB database using dedicated data logging nodes.
- Displays a real-time dashboard on web browsers (PC or mobile) with visual indicators, charts, and sensor metrics.
- Automatically sends email alerts if abnormal values are detected (e.g., pH out of range or sensor disconnection).
- Supports indirect image processing by receiving triggers from the Raspberry Pi or initiating machine learning models when needed..

2.4.4 InfluxDB software

InfluxDB is a specialized database software designed for time-series data, developed by the company InfluxData. It is widely used in IoT systems, sensor monitoring, industrial automation, and real-time data analytics.

Unlike traditional relational database management systems (such as MySQL or PostgreSQL), InfluxDB is optimized for storing, querying, and processing timestamped data that is continuously collected from sensors.

Figure 2.9 InfluxDB software

Key features of InfluxDB:

- Real-time data storage: InfluxDB can record millions of sensor data points with precise timestamps, ensuring high accuracy and fast write speed.
- Powerful querying with InfluxQL: Users can filter, aggregate, compute averages, extremes, rate of change, and more, all based on specific time intervals.
- Seamless IoT integration: It supports communication with platforms such as Node-RED, MQTT, Telegraf, and Python, making it easy to connect with devices like ESP32 and Raspberry Pi.

- Lightweight and efficient storage: InfluxDB can run directly on small devices like Raspberry Pi while still maintaining high performance for data storage and retrieval.
- Data visualization support: It integrates well with Node-RED Dashboard and graphing tools like Grafana to generate real-time charts and insights.

In the system described in this project, InfluxDB plays a central role in storing data collected from sensors and microcontrollers. Specifically:

- The ESP32 transmits data from sensors (temperature, pH, TDS, DO) via the MQTT protocol to a Raspberry Pi running InfluxDB.
- The data is recorded with exact timestamps, allowing for precise monitoring of environmental changes in the algae cultivation system.
- Users can query and visualize this data through the Node-RED Dashboard for intuitive tracking of the algae growth process.

Moreover, the historical data stored can be used as input for training machine learning models, enabling prediction of algae health and detection of abnormalities.

2.5 DATA TRANSMISSION METHODS IN THE SYSTEM

2.5.1 MQTT Communication

MQTT (Message Queuing Telemetry Transport) is a lightweight, efficient, and widely used communication protocol in Internet of Things (IoT) systems. It is specifically designed for collecting data from numerous devices and transmitting it to a central monitoring server in a fast, stable, and bandwidth-efficient manner.

- The protocol operates on a “Publish – Subscribe” model through an intermediary server known as the MQTT Broker, in which:
- Devices such as ESP32 publish sensor data under predefined topics.
- Applications or services such as Node-RED or InfluxDB subscribe to these topics to receive the published data.

- This model offers high scalability, decoupling between data producers and consumers, and ensures efficient data flow in real-time monitoring systems.

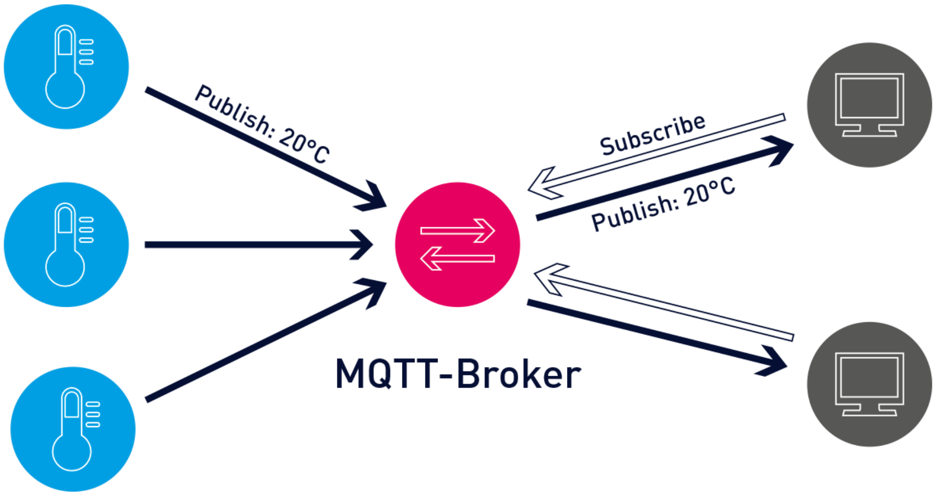


Figure 2.10 MQTT Communication

Key features of MQTT:

- **Low bandwidth consumption:** Lightweight message format, ideal for wireless networks or devices with limited computational resources.
- **High reliability:** Supports message acknowledgment with multiple Quality of Service (QoS) levels, ensuring no data loss during transmission.
- **Real-time performance:** Fast response time and low latency, suitable for applications requiring immediate feedback.
- **Cost-effective and easy to implement:** Can be easily deployed on low-power devices such as Raspberry Pi and supports multi-platform integration.
- **Good scalability:** New devices can be seamlessly integrated into the system by correctly configuring the corresponding topic.

Application of MQTT in this project:

- Transmitting sensor data (temperature, pH, TDS, DO) from ESP32 to the Raspberry Pi server.
- Enabling communication between ESP32 and Node-RED, allowing real-time data visualization and storage in InfluxDB.

- Sending image processing signals or system alerts when anomalies are detected, such as aeration failure or critical deviations in environmental parameters.

Base on MQTT, the system achieves high communication efficiency, conserves bandwidth, and ensures the accurate and stable delivery of real-time data.

2.5.2 UART Communication

UART (Universal Asynchronous Receiver/Transmitter) is one of the most commonly used and simplest serial communication protocols in embedded systems. This protocol enables two devices to transmit and receive data over two main signal lines: TX (transmit) and RX (receive), without requiring a shared clock signal. This makes UART ideal for low- to medium-speed communication, especially in systems where wiring simplicity is important.

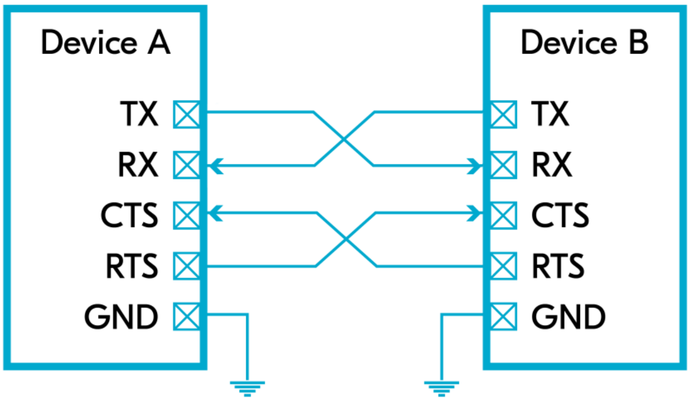


Figure 2.11 UART Communication

UART operates by sending data bit by bit in a structured frame, which typically includes a start bit, data bits, an optional parity bit, and one or more stop bits. The transmission speed is determined by the baud rate (e.g., 9600 or 115200 bps), which must be synchronized between the sender and the receiver.

In the algae monitoring system, UART communication is used for the following purposes:

- Connecting the DO-S20 sensor (RS485 output): Through an RS485–TTL converter module, the sensor data (DO, pH, and temperature) is received by the ESP32 microcontroller via UART.
- Reading the Gravity TDS sensor: Some versions of this sensor support both analog and UART interfaces, allowing more accurate digital data transmission to the ESP32.
- Communication between the ESP32 and Raspberry Pi: In certain situations, UART is used to transmit control signals or to trigger image processing tasks on the Raspberry Pi, especially when MQTT is not used.

UART offers a straightforward setup and reliable performance for short-distance communication with minimal interference. It is particularly effective for connecting industrial-grade sensors and microcontrollers in the algae farming IoT system.

2.5.3 Modbus communication

Modbus is a widely used industrial communication protocol designed for data exchange between control and monitoring devices such as PLCs, sensors, measurement instruments, and embedded controllers. It was initially developed in 1979 by Modicon (now a part of Schneider Electric) and has since become an open standard extensively adopted in the field of industrial automation and control.

Modbus is characterized by its simple data structure, ease of implementation, and compatibility with microcontroller-based systems, embedded platforms, and SCADA systems. The protocol enables a master device to communicate with one or more slave devices through the transmission and reception of structured data frames.

Modbus supports multiple transmission standards, with two primary forms:

- Modbus RTU (Remote Terminal Unit): Operates over serial communication lines such as RS485 or RS232, using binary-encoded data to enhance transmission efficiency.
- Modbus TCP: Operates over Ethernet networks, enabling data exchange via the TCP/IP protocol—suitable for modern monitoring and control systems.

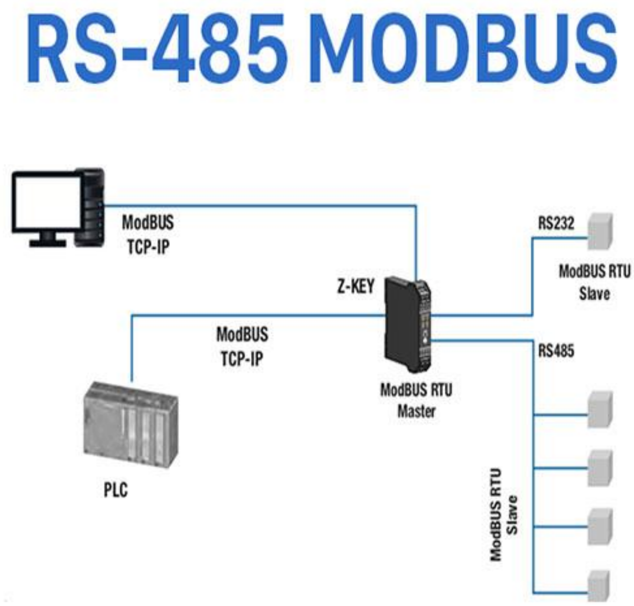


Figure 2.12 Modbus communication

In the smart algae farming system, Modbus RTU over RS485 is commonly employed for communication with industrial-grade sensors such as DO and pH probes, or external control modules. This is due to its robust data transmission, long-range capability (up to several hundred meters), and support for multi-device communication on a single bus.

Key advantages of Modbus include:

- Easy integration with microcontroller platforms (e.g., ESP32, STM32, etc.)
- Compatibility with a wide range of standard industrial devices
- Simple data frame structure, enabling fast processing
- Support for various data types (integers, floating-point numbers, status bits, etc.)

Thanks to these features, Modbus is an ideal protocol for connecting sensors and peripheral devices in IoT-based algae monitoring systems, ensuring reliable, accurate, and scalable data communication.

2.6 ACTUATORS IN THE SYSTEM

2.6.1 Nutrient pump and drain valve

The 365 DC 12V pump is a type of mini centrifugal pump commonly used in small-scale water or liquid pumping applications. With its compact design, lightweight structure, affordable cost, and stable operation at a 12VDC power source, this device is a suitable choice for automated electronic control systems that require a consistent and continuous flow.

Figure 2.13 365 DC 12V pump

Basic specifications of the 365 12VDC pump:

- Operating voltage: 12VDC
- No-load current consumption: ~0.23 A
- Flow rate: 2 – 3 liters/minute
- Output pressure: 1 – 2.5 kg/cm²
- Suction depth: 1 – 2.5 meters
- Inlet/outlet diameter: 8 mm (outer diameter)
- Design lifespan: approximately 2 – 3 years (under normal operating conditions)
- Weight: ~111 g
- Motor type: brushed DC motor type 365

In the smart algae cultivation monitoring and management system, the pump plays a central role in the process of supplementing nutrients into the culture tank. When the

TDS concentration in the environment drops below the acceptable threshold (due to harvesting, evaporation, or nutrient absorption), the microcontroller activates the pump to deliver nutrient solution from the storage tank into the cultivation system. Combined with a solenoid valve, this supplementing process is automated, precise, and optimized.

Using the 365 pump brings several significant advantages to the system: the device operates stably at low voltage, can be easily controlled by relays through the ESP32 microcontroller, and supports a simple control circuit design. Additionally, with a moderate flow rate and sufficient pressure, the pump effectively delivers nutrients over short distances without causing excessive water disturbance in the tank. It is also widely available on the market, easy to replace or repair, and aligns well with the goal of developing a cost-effective and sustainable system for laboratory or small-scale commercial use.

2.6.2 RESUN ACO 002 25W Air Pump

In the algae cultivation system, dissolved oxygen (DO) plays a crucial role in sustaining the life activities and growth of algal cells. Particularly for Spirulina—an aerobic microalgae species—adequate oxygen supply is a prerequisite for stable photosynthesis and biomass production.

The RESUN ACO 002 25W air pump functions as a key actuator to generate dissolved oxygen in the culture tank by injecting air into the water through diffusers, forming fine air bubbles that rapidly disperse.

Vai trò chính:

- Tăng hàm lượng DO trong nước, hỗ trợ tảo phát triển tốt.
- Tạo dòng lưu chuyển nhẹ trong bể, giúp tảo không bị lắng và phân bố đều ánh sáng.
- Hỗ trợ quá trình trao đổi khí CO_2 – O_2 trong môi trường nuôi.
- Góp phần phát hiện lỗi hệ thống khi xử lý ảnh không phát hiện bọt khí.

Figure 2.14 RESUN ACO 002 25W Air Pump

Technical specifications:

- Device model: RESUN ACO 002 25W
- Rated power: 25W
- Airflow rate: 40 L/min
- Operating voltage: 220–240V / 50–60Hz
- Number of air outlets: 6
- Air tubing: 3-meter Φ8mm air hose
- Operating mechanism: Electromagnetic piston pump
- Noise level: < 40 dB
- Brand origin: China

The air pump selected for the system is capable of delivering a stable oxygen supply and operating continuously 24/7, which meets the specific demands of algae cultivation requiring a consistent and prolonged airflow. The device features an insulated casing, high durability, and low heat generation during extended operation. Despite its low power consumption, the pump offers high efficiency, contributing to significant energy savings. Additionally, its simple construction allows for easy installation and maintenance. The quiet operation and low vibration help maintain a stable culture environment without disrupting algal growth.

2.6.3 Warm-spectrum LED light for supporting nighttime photosynthesis

In algae cultivation systems, light is an essential factor to ensure efficient photosynthesis. During nighttime or under conditions lacking natural sunlight, artificial light sources must be used to support the synthesis of organic compounds within algal cells, thereby sustaining and promoting growth.

The system employs warm white LED strip lights (3000K) to simulate the red region of the solar spectrum, which effectively supports the photosynthetic process. This type of light is well-suited to Spirulina algae, which are sensitive to red and yellow wavelengths ranges that can penetrate deeper into water environments.

Technical specifications of the LED light:

- Model: LED Strip 2835 10W/m
- Input voltage: 24VDC
- Power consumption: 10W/m
- Length: 5m/roll
- Current: 2.08A
- Luminous flux: 600 lumens/m
- LED type: SMD 2835 – Seoul semiconductor chip
- Color temperature (CCT): 3000K – warm white
- Color rendering index (CRI): > 80
- LED dimensions: Width 12mm, thickness 4mm
- Copper core thickness: 3oz = 105 microns
- Waterproof rating: IP65 – suitable for humid environments
- Safety certifications: ROHS / EMC
- Operating temperature: -10°C to 40°C
- Warranty: 1 year

Figure 2.15 Strip LED 3000K

The LED lighting system employed in the model offers several outstanding advantages, making it well-suited for algae cultivation environments. Firstly, the lights emit an optimized spectral range for photosynthesis, particularly effective for algae species that are sensitive to red–yellow wavelength regions. Despite their low power consumption, the devices exhibit high luminous efficacy, contributing significantly to energy savings. In addition, with an IP65-rated waterproof standard, the lights ensure safe operation in humid conditions. The LED structure incorporates thick copper cores and high-quality chips, providing extended lifespan. Its flexible design also allows for easy installation in various positions within the cultivation tanks.

CHAPTER 3. SYSTEM DESIGN AND MONITORING DEVICE MODEL

3.1 MONITORING SYSTEM

3.1.1 System block diagram

The system block diagram provides a visual representation of the main components within the electrical system and how they interact with one another. By dividing the system into distinct functional blocks, the diagram clarifies the role of each component as well as the connections and data exchanges between the elements during operation.

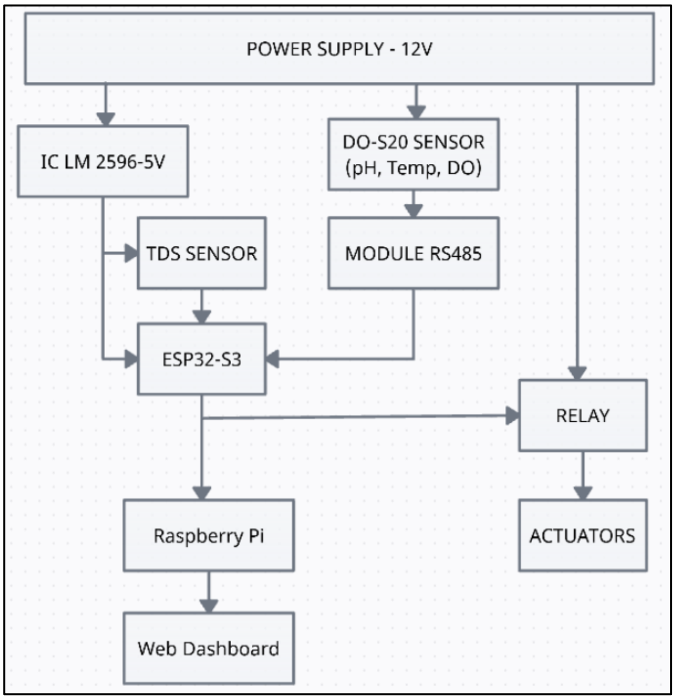


Figure 3.1 System block diagram

3.1.2 Power supply block

The power supply block is a critical component of the entire system, ensuring stable and appropriate voltage delivery for the operation of electronic components. In the IoT-based algae monitoring system, the main supply voltage is 12 V DC, which is divided into three separate branches, each serving a specific function:

a) 5 V DC branch – supplying auxiliary devices.

The 12 V DC input is stepped down to 5 V using an LM2596 voltage regulator module. This 5 V output powers the following components:

- The Gravity TDS sensor, which operates at 5 V and returns an analog signal to the ESP32 through the ADC pin.
- The 5 V relay coil, used to control actuators such as the electric ball valve.
- The CH340C module, which facilitates USB communication and code uploading to the ESP32.

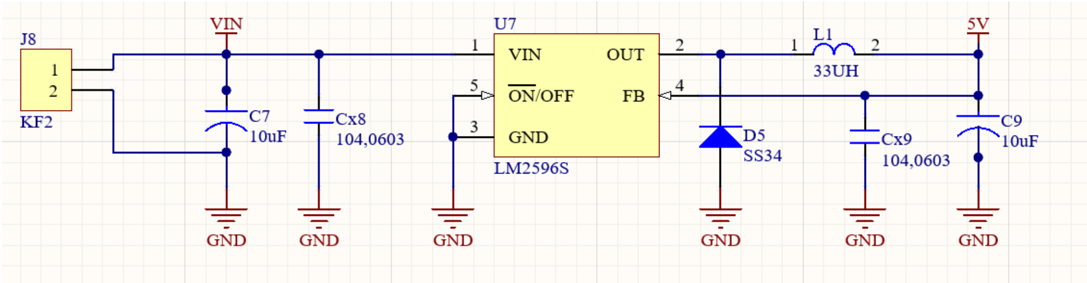


Figure 3.2 Power supply block

b) 3.3 V DC branch – supplying the microcontroller and logic circuits

The 5 V output from the LM2596 is further regulated down to 3.3 V DC using the LM1117-3.3V voltage regulator. This voltage branch directly supplies power to:

- The ESP32-S3 WROOM-32 microcontroller via its VCC pin.
- The MAX3485 (RS485-TTL) module, which operates at a 3.3 V logic level to communicate with the DO-S20 sensor.
- Other logic components that require 3.3 V operation, such as indicator LEDs, push buttons, and similar elements.

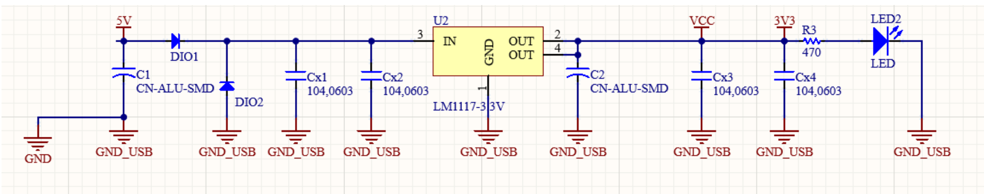


Figure 3.3 Branch 3.3 V DC

c) 12 V DC branch – directly powering high-power devices

Certain devices that require higher voltage and greater current are powered directly from the 12 V DC input supply. These include:

- The DO-S20 sensor, which operates at 12 V and communicates via RS485.
- High-power actuators controlled through MOSFETs or relays, such as:
  - 25W aeration pump
  - Nutrient dosing pump
  - 3000K LED strip for photosynthesis support
  - Electric ball valve

3.1.3 Microcontroller block

The microcontroller block serves as the central unit responsible for processing and coordinating all operations of the algae cultivation environmental monitoring system. In this system, the microcontroller used is the ESP32-S3 WROOM-1U5, a high-performance chip with integrated Wi-Fi, capable of real-time signal processing and efficient IoT connectivity.

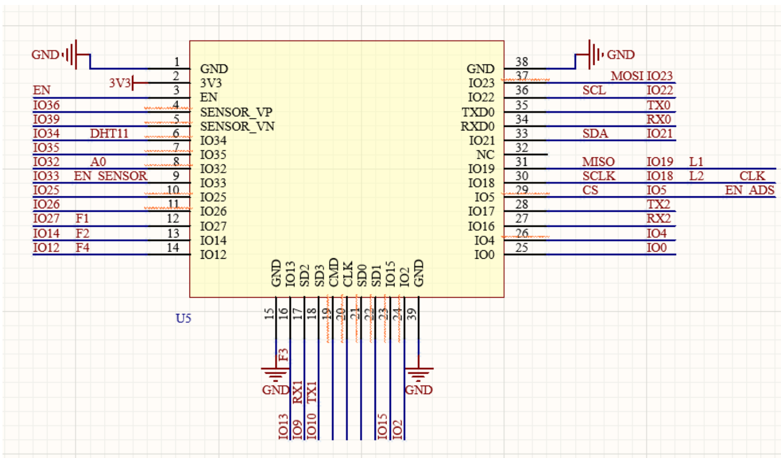


Figure 3.4 Microcontroller block

Roles and functions:

- Receiving data from various sensors, including TDS, DO, pH, temperature, and water level sensors.
- Processing data and making control decisions for devices such as pumps, valves, lights, and aerators.

- Transmitting environmental data to a server via MQTT for storage and monitoring.
- Supporting parallel communication through multiple protocols: ADC, UART, RS485, Wi-Fi, and GPIO outputs.

The use of the ESP32-S3, with its high performance, large memory capacity, integrated Wi-Fi, and multi-protocol support, enhances the system's reliability and enables flexible scalability in practical IoT applications.

3.1.4 Sensor block

The sensor block is responsible for collecting key environmental parameters during the algae cultivation process, including water quality and algal growth conditions. The collected data is transmitted to the ESP32 microcontroller for processing and subsequently sent to the monitoring server.

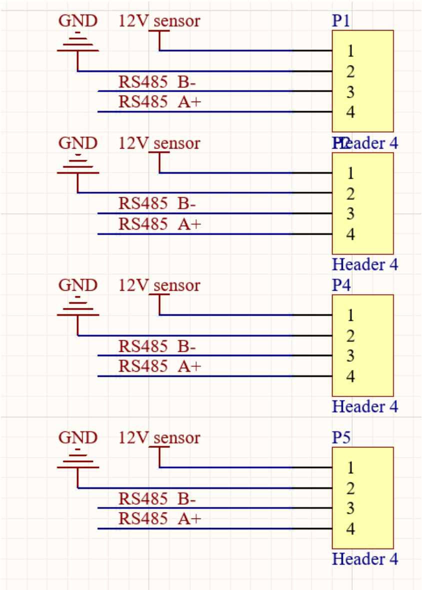


Figure 3.5 Sensor block

The system employs two main types of sensors:

- **TDS sensor (DFRobot Gravity):** This sensor operates at 5 V and outputs an analog signal proportional to the concentration of total dissolved solids (TDS) in the water. The analog signal is fed into the ESP32's ADC pin, where it is measured and converted into a TDS value using an appropriate calibration formula.

- **Integrated DO-S20 sensor (RS485):** This sensor is capable of simultaneously measuring three parameters: dissolved oxygen (DO) concentration, pH level, and water temperature. It operates at 12 V and communicates via the RS485 protocol. A MAX3485 converter module is used to convert the RS485 signal into a 3.3 V UART TTL signal compatible with the ESP32.

In addition to the two primary sensors mentioned above, the system also includes an electronic float sensor to detect low water levels in the tank. When the water level drops below the allowable threshold, the sensor sends a logic-level signal to the ESP32 to trigger an alert or activate the nutrient pump.

Sensor data is periodically collected by the ESP32, processed, and transmitted to the Raspberry Pi via the MQTT protocol. The integration of multiple sensor types enables comprehensive environmental monitoring, ensuring optimal conditions for algae cultivation.

3.1.5 Actuator block

The actuator block in the system is responsible for executing physical control actions such as water pumping, aeration, lighting, and opening/closing of nutrient valves. These actuators operate on a 12 V DC power supply and are directly controlled by the ESP32-S3 microcontroller through its GPIO pins.

The electric ball valve is controlled via a 5 V relay. When the ESP32 activates the relay, the valve opens or closes to allow nutrient solution to flow into the cultivation tank. In addition, three other devices—the peristaltic pump, the aeration pump, and the 3000K LED strip—are controlled using IRF3205 MOSFETs.

All actuators are powered by a dedicated 12 V supply to ensure that they do not interfere with the control circuitry. This power separation enhances system stability and allows timely responses when environmental adjustments in the algae tank are required.

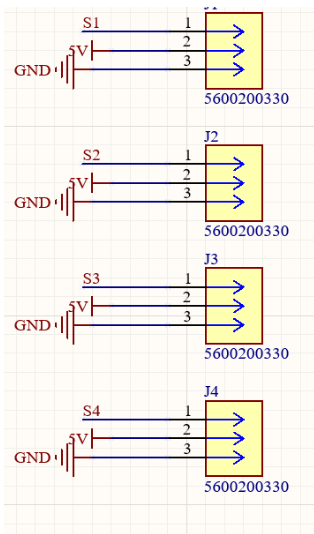


Figure 3.6 Actuator block

3.1.6 PCB design

The printed circuit board (PCB) design process was carried out using Altium Designer, with the goal of transforming the schematic diagram into a stable, compact, and easy-to-assemble hardware system. Initially, a complete schematic was developed, including all functional blocks such as the power supply, ESP32-S3 microcontroller, TDS and DO-S20 sensors, relay block, MOSFETs, and connectors.

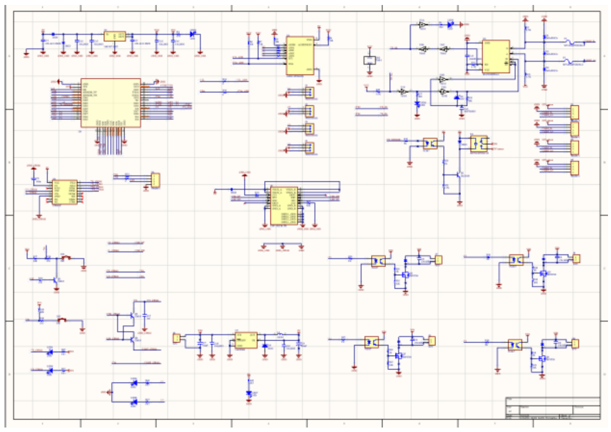


Figure 3.7 Design schematic

Next, the components were logically arranged on the PCB layout: the power supply block was placed near the 12 V input terminal; the microcontroller was positioned at the center to facilitate convenient signal routing; the sensor connectors were grouped on one side to simplify wiring; and the actuator block (relays and MOSFETs) was physically isolated from the control circuits to minimize power-related interference.

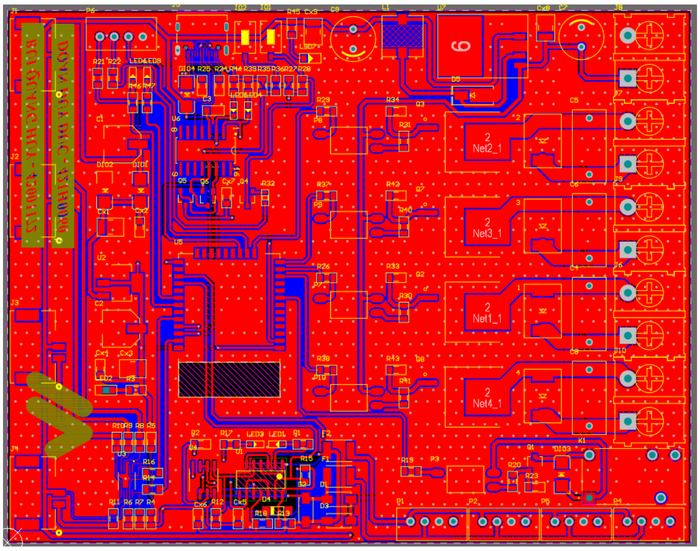


Figure 3.8 Routing process

The routing process was implemented using a two-layer copper layout. The top layer (red) was primarily reserved for control signal traces, while the bottom layer (blue) served mainly as a ground (GND) plane and for routing high-current power lines. The 12 V power traces supplying high-load devices such as the aerator, pump, and LED strip were widened appropriately to handle higher current and prevent voltage drops. In contrast, signal lines from sensors and control signals were kept short and compact to minimize crosstalk. Decoupling capacitors were placed close to the power pins of integrated circuits and sensor modules to stabilize the voltage and suppress transient noise during operation.

Finally, after completing the component placement and routing stages, the design was verified using the Design Rule Check (DRC) function to detect and eliminate any layout errors. The Gerber files, drill files, and bill of materials (BOM) were then generated to support the PCB manufacturing and assembly processes in practice.

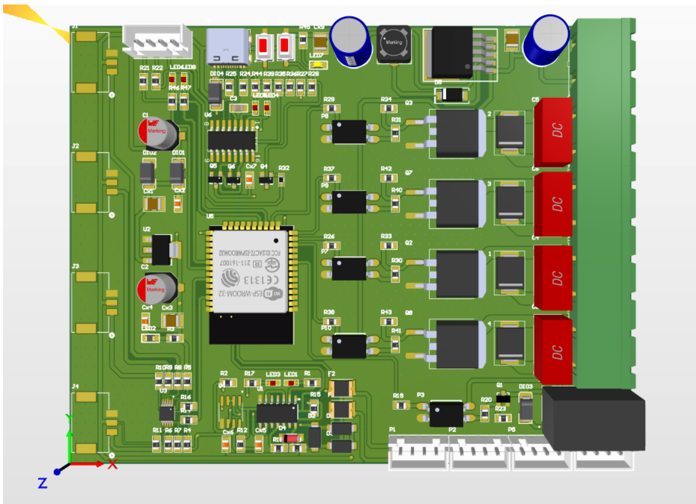


Figure 3.9 3D PCB

3.2 OBSERVATION MACHINE MODEL

3.2.1 Design of protective enclosure for Raspberry Pi

In the algae monitoring system, the Raspberry Pi 4 serves as a central embedded computer, processing sensor data, storing information, and controlling the monitoring interface. Since the device operates continuously in a high-humidity environment and may be exposed to water or dust, designing a dedicated protective enclosure is essential to ensure durability, stability, and safety for the circuit board.

Autodesk Fusion 360 software was used to design the 3D enclosure based on the standard dimensions of the Raspberry Pi 4. The design meets the following criteria:

- **Physical protection:** The enclosure fully covers the circuit board, preventing direct contact with moisture, dust, or insects.
- **Heat dissipation:** Ventilation slots are added on both sides and the top to allow air circulation and passive cooling.
- **Ease of operation:** The enclosure has a sliding or screw-removable lid, supporting quick access for updating the memory card, connecting cables, or replacing components.

- **Access to connection ports:** Precise placement of holes for HDMI, USB, LAN, USB-C, and camera jack ensures no obstruction to cables during operation.
- **Secure mounting:** The design includes screw holes or fixing tabs for firmly attaching the enclosure to the monitoring system frame.

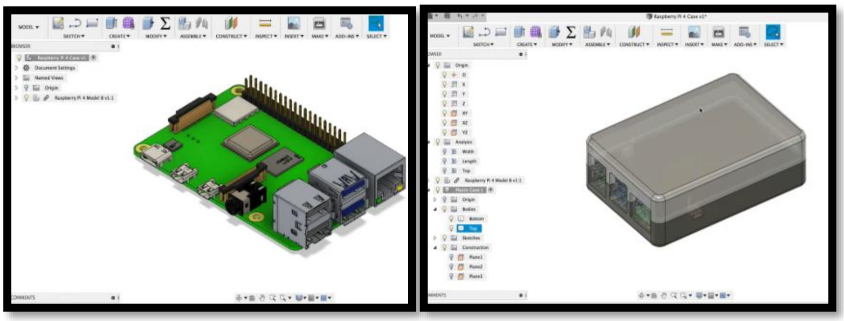


Figure 3.10 Design of protective enclosure for Raspberry Pi on Autudesk Fusion 360

The proposed fabrication materials are 3mm thick transparent acrylic (mica) or 3D-printed plastics such as PLA/ABS, depending on construction conditions. After completing the model, the drawings are exported in DXF format (for laser cutting acrylic) or STL format (for 3D printing), ensuring accuracy and compatibility with other devices in the system.

The enclosure design not only protects the hardware but also contributes to enhancing the professionalism, aesthetics, and overall stability of the algae monitoring system.

3.2.2 Design and arrangement of devices inside the technical enclosure

To ensure safety, durability, and aesthetics for the system, a waterproof (IP65) technical enclosure is used to house all control and processing devices. The enclosure measures 16 × 27 cm, providing sufficient space to accommodate the main electronic components of the algae environmental monitoring system.

Figure 3.11 Plastic enclosure for device housing

The devices are arranged according to the principles of neatness, ease of maintenance, and clear separation between the power control circuits and communication modules. Specifically:

- The Raspberry Pi 4 is positioned at a higher location, fixed using a bracket or screw holes on the enclosure's mounting surface. USB, LAN, and HDMI ports are routed to the enclosure's side through pre-cut holes, facilitating configuration and peripheral connections.
- The main control board, measuring 120 mm × 94 mm, is designed to fit snugly within the technical enclosure. All components such as the ESP32-S3, RS485 module, TDS sensor, LM2596 power supply, and relay are arranged tidily.
- Signal and power cables are bundled neatly using heat shrink tubing or zip ties, grouped clearly to simplify monitoring and maintenance.
- Ventilation holes or cooling slots can be drilled on the enclosure lid or sides to prevent heat buildup for the Raspberry Pi and power circuits during prolonged system operation.
- The inner side of the enclosure lid may have a layout diagram or numbered labels for connectors, aiding technicians in easy inspection and maintenance.

With this scientific and space-optimized arrangement, the technical enclosure not only protects the devices safely but also enhances the stability and reliability of the entire system under real operating conditions in the algae farming environment.

CHAPTER 4. FABRICATION OF THE MODEL AND DEPLOYMENT OF THE ALGAE CULTIVATION SYSTEM

4.1 FABRICATION OF THE MODEL

4.1.1 Order PCB processing at the factory

After completing the schematic design and component layout on Altium Designer software, the team proceeded to export the PCB manufacturing file set, including the Gerber file, drill file, and layer stackup. The files were compressed into a single .zip package to send to the manufacturer.

To ensure the quality of processing and optimize costs, the team chose the PCB manufacturing service from the online platform JLCPCB. This is one of the popular global PCB manufacturing service providers, supporting online ordering, Gerber file preview, flexible specification options, and short production time.

The ordering process is carried out in the following steps:

a) Prepare manufacturing files.

From the Altium Designer design interface, the team uses the Fabrication Outputs function to export Gerber files and drill files.

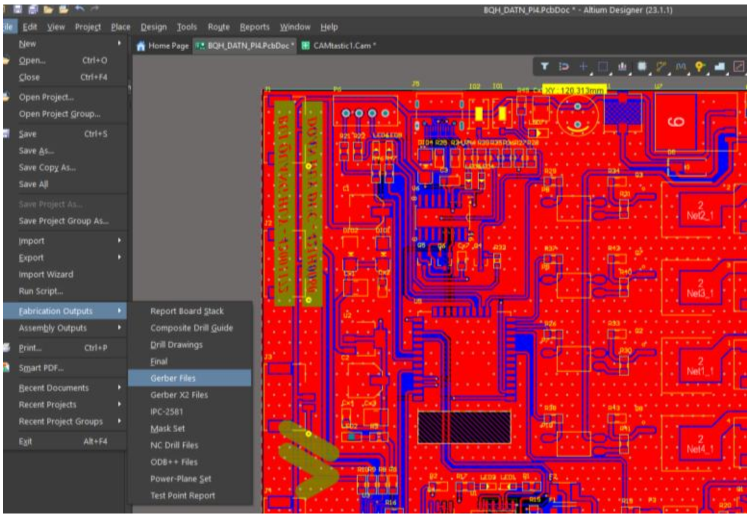


Figure 4.1 Prepare manufacturing files.

Layer configuration includes:

- Top layer, Bottom layer
- Top/Bottom Soldermask
- Top/Bottom Silkscreen
- Mechanical Layer
- Drill drawing

After checking, the entire file is compressed into a .zip file in the correct format required by the manufacturer.

b) Upload the file and configure the order on the JLCPCB platform.

Go to https://jlcpcb.com and select the "Order Now" feature. Then, the .zip file is uploaded to the system, and a preview (Gerber Viewer) is displayed to visually check the circuit diagram before ordering.

The circuit specifications are configured as follows:

- Number of layers: 2 layers
- Board thickness: 1.6 mm
- Copper layer thickness: 1 oz (35 µm)
- Soldermask color: Green
- Surface treatment: HASL (Hot Air Solder Leveling)
- Circuit size (L×W): According to the actual design (~121 mm × 9.6 mm)
- Order quantity: 5 copies

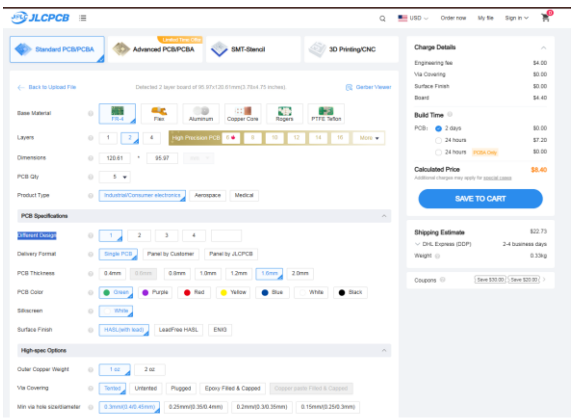


Figure 4.2 Order on the JLCPCB platform

After confirming the configuration information, the team rechecks the routing of circuit layers, signal lines, drill holes, and lettering layers to avoid errors before moving to the payment step.

c) Order, track, and check the finished product.

After completing the configuration, the team proceeds to pay via PayPal or international credit card. The selected shipping unit is DHL to ensure fast delivery time (within 5–7 working days). The system provides an order tracking code to update the shipping status.

After receiving the finished PCB, the team conducts a preliminary inspection of technical factors such as

- Sharpness of copper layer and lettering layer
- Position of drill holes according to design
- No signs of solder mask peeling or short circuit

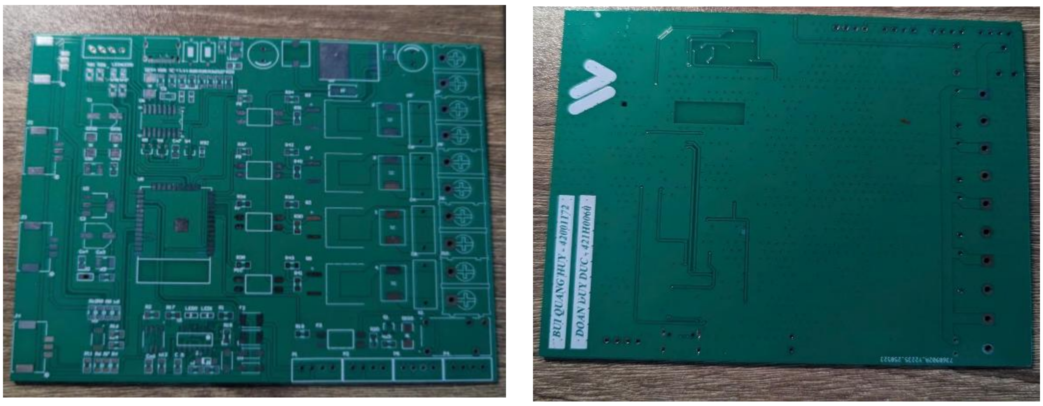


Figure 4.3 Actual PCB circuit

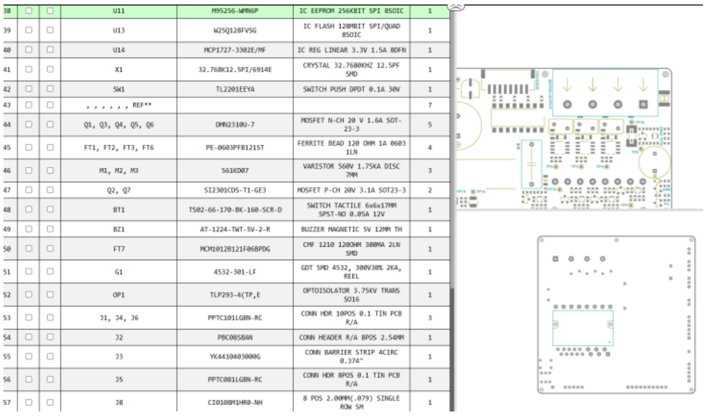
The board after testing is confirmed to meet the requirements and is ready for the component soldering stage.

4.1.2 Welding components

a) Prepare components and equipment.

After receiving the completed PCB, the next step is to fully prepare the electronic components for circuit assembly. Preparing components is an important step to ensure that the soldering process is continuous and accurate, avoiding omissions or errors that affect circuit performance.

First, the team compares the BOM (Bill of Materials) list with the component layout diagram (PCB Layout) to accurately determine the types of components needed, including resistors, capacitors, diodes, transistors, ICs, microcontrollers, headers, power jacks, communication modules, and connectors (terminal blocks). Each type of component is arranged in separate boxes or labeled for easy identification.



38	☐	☐	U11	M95256-WMN6P	IC EEPROM 256KBIT SPI 8SOIC	1
39	☐	☐	U13	W25Q128FVSG	IC FLASH 128MBIT SPI/QUAD 8SOIC	1
40	☐	☐	U14	MCP1727-3302E/MF	IC REG LINEAR 3.3V 1.5A 8DFN	1
41	☐	☐	X1	32.768K12.5PI/6914E	CRYSTAL 32.7680KHZ 12.5PF SMD	1
42	☐	☐	SW1	TL2201EEYA	SWITCH PUSH DPDT 0.1A 30V	1
43	☐	☐	, , , , , , REF**			7
44	☐	☐	Q1, Q3, Q4, Q5, Q6	DMN2310U-7	MOSFET N-CH 20 V 1.6A SOT-23-3	5
45	☐	☐	FT1, FT2, FT3, FT6	PE-0603PFB121ST	FERRITE BEAD 120 OHM 1A 0603 1LN	4
46	☐	☐	M1, M2, M3	561KD07	VARISTOR 560V 1.75KA DISC 7MM	3
47	☐	☐	Q2, Q7	SI2301CDS-T1-GE3	MOSFET P-CH 20V 3.1A SOT23-3	2
48	☐	☐	BT1	TS02-66-170-BK-160-SCR-D	SWITCH TACTILE 6x6x17MM SPST-NO 0.05A 12V	1
49	☐	☐	BZ1	AT-1224-TWT-5V-2-R	BUZZER MAGNETIC 5V 12MM TH	1
50	☐	☐	FT7	MCM1012B121F06BPDG	CMF 1210 120OHM 300MA 2LN SMD	1
51	☐	☐	G1	4532-301-LF	GDT SMD 4532, 300V30% 2KA, REEL	1
52	☐	☐	OP1	TLP293-4(TP,E	OPTOISOLATOR 3.75KV TRANS SO16	1
53	☐	☐	J1, J4, J6	PPTC101LGBN-RC	CONN HDR 10POS 0.1 TIN PCB R/A	3
54	☐	☐	J2	PBC08SBAN	CONN HEADER R/A 8POS 2.54MM	1
55	☐	☐	J3	YK4410403000G	CONN BARRIER STRIP 4CIRC 0.374"	1
56	☐	☐	J5	PPTC081LGBN-RC	CONN HDR 8POS 0.1 TIN PCB R/A	1
57	☐	☐	J8	CI0108M1HR0-NH	8 POS 2.00MM(.079) SINGLE ROW SM	1

Figure 4.4 Schematic to PCB Linkage

Components are preliminarily checked with a multimeter to determine the correct value and operating status before soldering. Some components, such as electrolytic capacitors, diodes, LEDs, etc., are polarized, so it is necessary to carefully check the installation direction to avoid reverse installation causing damage or short circuits after powering up. In addition, the team prepares the necessary tools and materials for the soldering process, including a stable temperature soldering iron (60–80 W), solder, tweezers, cleaning paper, thermal paste, insulating tape, and a component mounting board.

Finally, the work area is neatly arranged, with clear lighting and an anti-static tabletopto ensure the safety of sensitive semiconductor components such as microcontrollers and logic ICs. Careful and complete preparation helps reduce soldering time, increase accuracy, and limit technical errors during manual assembly.

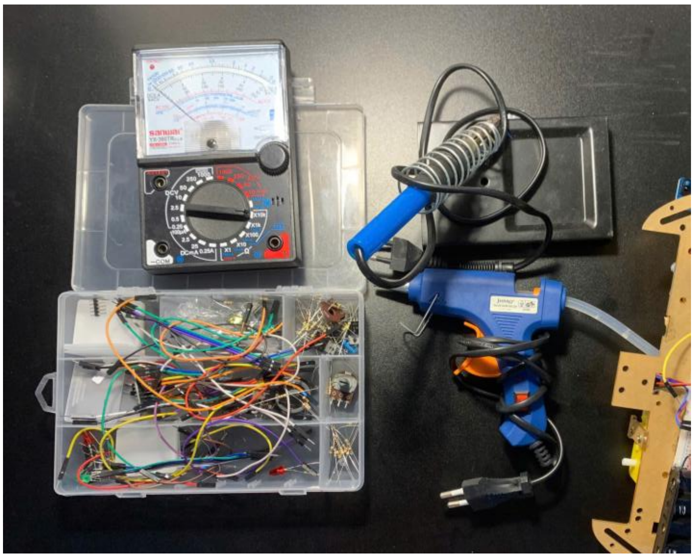


Figure 4.5 Prepare components

b) Soldering components to the circuit

After fully preparing components and tools, the team proceeds to manually solder the components onto the circuit board. The soldering process follows the principle of low to high components, from the center outwards, for ease of operation and to ensure accurate placement.

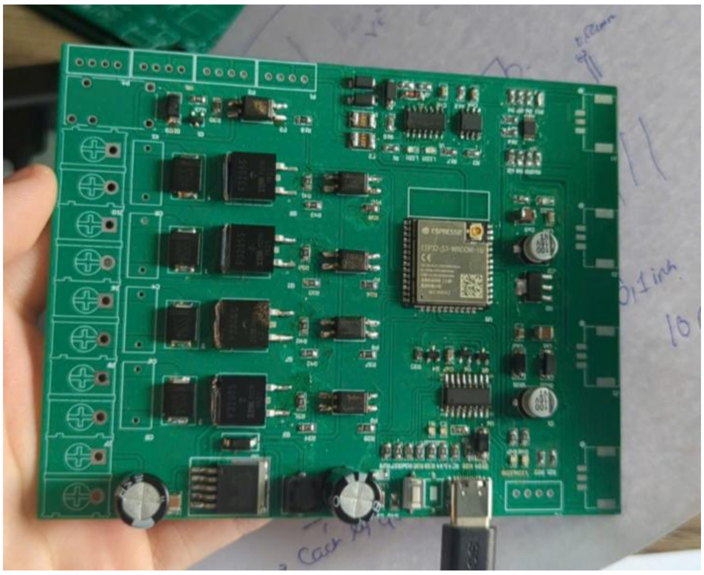


Figure4.6 Solder components to the circuit

Components such as resistors, ceramic capacitors, and diodes are soldered first, followed by ICs, MOSFETs, relays, power jacks, and header pins. During the soldering process, the soldering iron is adjusted to a suitable temperature (about 320–

350°C), ensuring that the soldering pins adhere firmly, without excess tin and without causing short circuits. For polarized components such as diodes, electrolytic capacitors, LEDs, etc., the team carefully checks the installation direction before fixing.

Once complete, the board is cleaned with isopropyl alcohol to remove excess flux and checked with a continuity tester. Soldering sites are inspected for defects such as cold soldering, short circuits, or insufficient pads. The circuit is then ready for power-up and functional testing.

4.1.3 Complete equipment assembly.

After soldering the components and checking the function of each circuit element, the final assembly process of the device is carried out. The main control board, including ESP32-S3, sensor modules (TDS, RS485), relay,,, and LM2596 power circuit, is firmly fixed to the technical box through plastic feet and insulating screws. The signal wires and power wires are bundled with zip ties and conduits to ensure aesthetics and reduce signal noise. The circuit is installed with a Raspberryryry Pi 4, a storagegege hard drive, a USBSBSB camera,,, and communication connections such as a powerer port, a USB port, RS485... All are routed and fixed in the box, ensuring that they do not move during operation. Finally, the box is sealed, the contact points are rechecked, and a test power supply is conducted to ensure the entire system operates stably before deploying to the real environment.

Figure 4.7 Model installation

4.2 DEPLOYMENT OF ALGAE CULTIVATION SYSTEM MODEL

4.2.1 Conditions for model implementation

The model is built in a closed warehouse space, covered with translucent plastic roofing to take advantage of natural light while limiting the high radiation intensity at noon, which is typical of summer in Vietnam. The closed space helps to better control environmental temperature factors and minimize the impact of wind, dust, or foreign organisms.

Figure 4.8 Survey of farming location

The breeding tank used is a 200-liter round plastic tank. The water source used is filtered and dechlorinated tap water. Nutrients are mixed manually based on a standardized formula with ingredients such as $NaHCO_3$, K_2HPO_4, $MgSO_4$, and trace elements, ensuring suitable pH and mineral content for the growth of Spirulina platensis algae.

4.2.2 Installation and configuration of technical systems

The hardware system includes

- ESP32-S3 microcontroller connecting sensors (DO, pH, temperature, TDS).
- DO-S20 sensor communicating with RS485; DFRobot analog TDS sensor.
- Relay and MOSFET controller to control aerators, pumps, and lighting.
- A camera taking pictures of the tank surface every 5 minutes, connected to a Raspberry Pi.

- Data is transmitted to Raspberry Pi via MQTT protocol, displayed via Node-RED, and saved to InfluxDB

Hệ thống phần cứng bao gồm:

- Vi điều khiển ESP32-S3 kết nối các cảm biến (DO, pH, nhiệt độ, TDS).
- Cảm biến DO-S20 giao tiếp RS485; cảm biến TDS analog của DFRobot.
- Bộ điều khiển relay và MOSFET để điều khiển máy sục khí, bơm, đèn chiếu sáng.
- Camera chụp ảnh bề mặt bể định kỳ 5 phút/lần, kết nối Raspberry Pi.
- Dữ liệu được truyền về Raspberry Pi qua giao thức MQTT, hiển thị qua Node-RED và lưu vào InfluxDB.

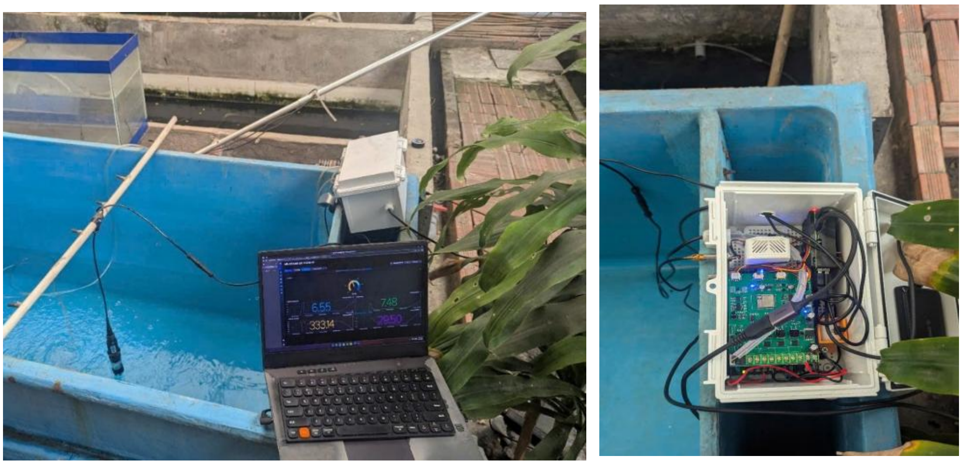


Figure 4.9 Installation and testing of monitoring equipment

The sensors are fixed at the center of the tank with a standard depth of 15–20 cm to ensure correct measurement of the algae biomass distribution area. The aerator and 3000K lighting are programmed to turn on/off according to a fixed schedule.

4.2.3 Trial rearing process

The first phase was to operate the system in an algae-free condition to test the stability of the connections, the accuracy of the data, and the continuous operation of the system. After a week of testing, the data from the sensors showed low noise, stable connections, and no communication errors. The tank was then cleaned, nutrients were added, and spirulina algae were stocked. The initial algae density was about 0.1 g/L. During the entire cultivation process, the system operated continuously 24/7 and collected data in real time.

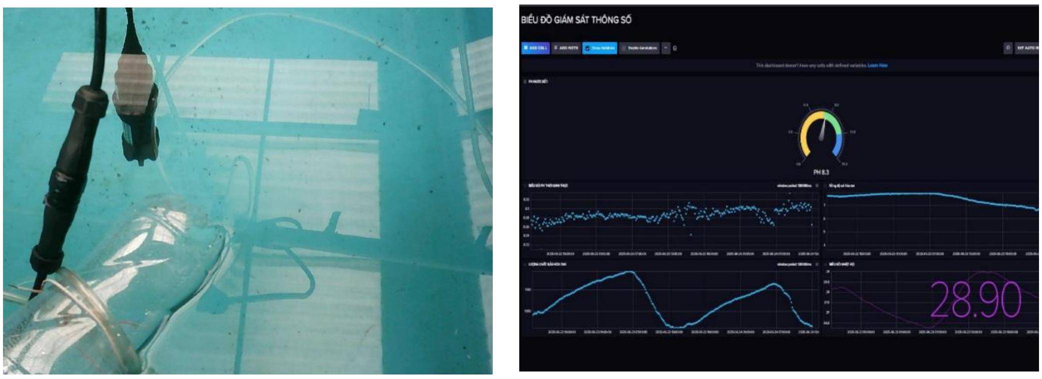


Figure 4.10 Data collection and storage

4.2.4 Data collection and analysis

Data is recorded in 3 main stages:

- Before stocking (clean water): Record background parameters such as pH, DO, and TDS in an environment without biomass.
- Growth stage: Parameters change over time due to photosynthesis and mineral consumption.
- Incident stage: Sometimes record local algae death (DO drops sharply, pH fluctuates), helping to verify the usefulness of the system in early warning.

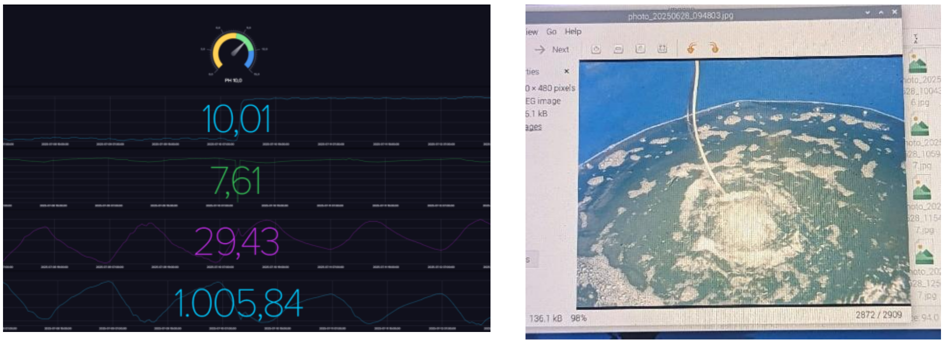


Figure 4.11 Data collected in the first 15 days

The camera system combined with image processing (YOLOv5) allows the recognition of air bubble density and surface color, serving to detect abnormalities or assess algae health.

4.2.5 Preliminary assessment

The initial experimental model has demonstrated the stability and operational efficiency of the technical system under actual algae cultivation conditions. Data collected from sensors (pH, DO, TDS, temperature) has high accuracy, accurately reflecting environmental fluctuations occurring during the algae growth process. The system operates fully automatically, allowing continuous monitoring without manual intervention, contributing to significantly reducing the workload of traditional monitoring.

In addition to quantitative data, the system also integrates a camera to take periodic photos and process images using a machine learning model, supporting the detection of abnormalities such as changes in surface color or reduced air bubble density—indicators directly related to the health status of algae biomass. The combination of sensor data and image information has created a comprehensive monitoring system, supporting multidimensional analysis and scalability for forecasting applications.

The implementation results show that the system has high potential for application in small- and medium-scale algae farming models. With reasonable implementation costs, a high automation level, and the ability to integrate artificial intelligence, the system is suitable for the trend of modernizing farming technology and developing sustainable green solutions in high-tech agriculture.

CHAPTER 5. TESTING AND RESULTS

5.1 ENVIRONMENTAL MONITORING EQUIPMENT TESTING

The monitoring system was tested to assess the level of compliance with technical requirements in monitoring water environment parameters in the smart algae farming system. Through the actual testing process, the device showed its ability to fully and accurately measure important indicators, including pH, DO (dissolved oxygen), TDS (total dissolved solids), and water temperature. The measured values are clearly displayed on the web interface, helping the operator to easily monitor in real time and intervene promptly when abnormalities appear in the farming environment.

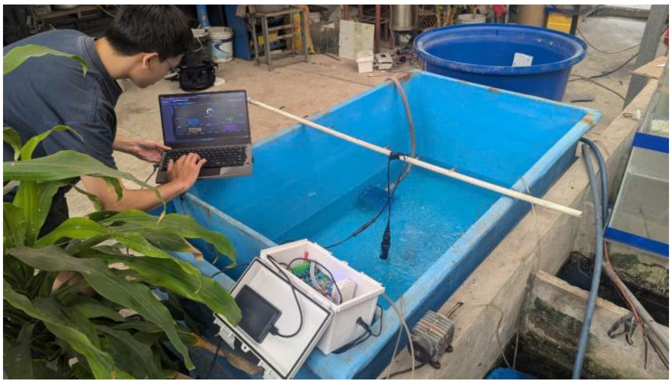


Figure 5.1 Environmental monitoring equipment inspection

The objective of the inspection process is to verify that the monitoring system meets the basic technical standards for sensor accuracy, continuous operation, signal stability, and safety in use. At the same time, check that functions such as data collection, signal transmission, display, and warning are working as originally designed. The results show that the device has high stability, fast response, and is suitable for deployment in small- to medium-scale practical algae farming models.

5.2 EXPERIMENTAL RESULTS

5.2.1 Experimental results of the algae cultivation process

a) System farming and operation process

The spirulina algae farming model is deployed in a 200-liter sealed plastic tank located in a warehouse with a corrugated iron roof for natural light. The environment is prepared by pre-mixing the nutrient solution according to the standard formula ($NaHCO_3$, urea, $MgSO_4$...) with clean filtered water, then adjusting the pH and TDS appropriately (pH ~7.0, TDS ~1,000 ppm) before releasing the seeds.

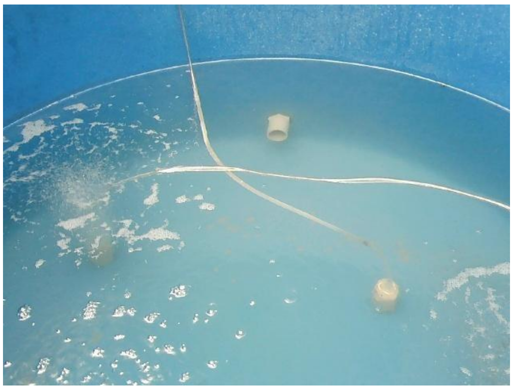


Figure 5.2 The first day of algae cultivation

During 15 days of continuous farming, the system operated stably with the following components:

- Continuous aeration 24/7 with an aeration pump and airstone, ensuring that algae always circulate and absorb nutrients.
- Sensors measuring pH, DO, TDS, and temperature transmit data via ESP32 to Raspberry Pi.
- Data is displayed in real-time on the Node-RED dashboard and saved to InfluxDB.
- The nutrient replenishment system is automatically activated if TDS or pH drops beyond the set threshold.

Monitoring results show that the environment is stable, algae grow evenly, the water changes from light green to dark green, and the clarity gradually decreases, reflecting the increase in biomass density.

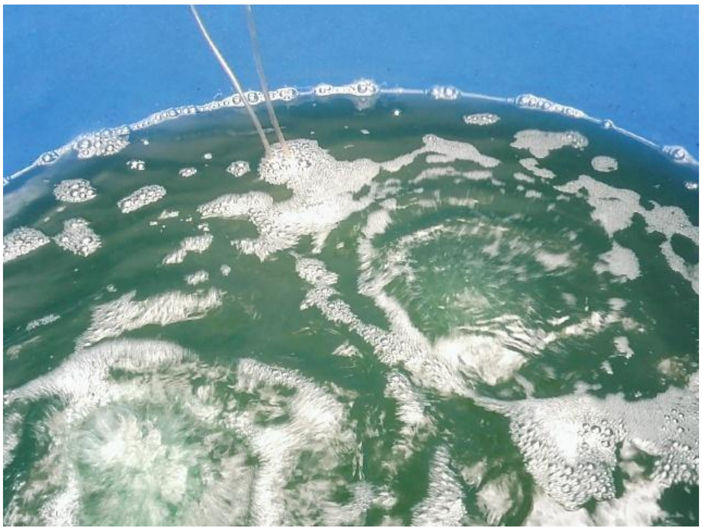


Figure 5.3 The 15th day of algae cultivation

b) Algae biomass filtration and collection process

After 15 days, the system is paused to filter and collect biomass.

- Using a specialized filter net of 50–100 µm, manually filter with the bottom drain valve.
- Water is led through the filter net, retaining large-sized and high-density algae.
- The amount of water after filtration (~70–75%) is pumped back into the tank to reuse the environment, retain algae that have not met quality standards, and serve as a foundation for the next batch of culture.

c) Assessing the quality of algae after filtration

Algae are clearly divided into two quality levels:

- Standard algae: dark green, long fibers, settle quickly—accounting for about 25–30% of the total. This is the part retained for drying or as a sample for analysis.
- Undeveloped algae: pale color, short fibers, dispersed—usually young biomass, not yet in its full cycle. This part is retained in the circulating water to continue growing.

In addition, the camera and AI system support recording the gradual change in water color over time, supporting visual assessment of growth and deciding the appropriate time to harvest algae.

d) Advantages and conclusions

Reusing water and young biomass not only helps save resources but also helps maintain healthy algae strains, without having to buy new ones, while shortening the setup cycle of each batch. This contributes to the goal of sustainable development and circular economy in the algae farming model.

5.2.2 Bubble detection results using machine learning model

In the algae culture monitoring system, ensuring the stable operation of the aerator is of utmost importance. To automate the monitoring of this condition, the project applied computer vision combined with a deep learning model—specifically YOLOv5—to identify air bubbles appearing on the surface of the culture tank. The model was trained from a real image dataset collected during the model deployment process.

a) Implementation process:

- Images are captured by a camera mounted on the tank every 5 minutes and then transmitted to the Raspberry Pi 4.
- Input images are fed into the trained YOLOv5 model.
- The model returns results including the location (bounding box) and confidence score of the area identified as a bubble.

Figure 5.4 Training ML to detect bubbles

b) Quantitative results:

After training the YOLOv5 model to detect air bubbles in the algae culture system, the testing results on the validation dataset of 24 images (157 objects) showed the following performance

Table 1. Model accuracy evaluation

Chỉ số	Giá trị	Diễn giải
Precision (P)	0.589	Khoảng 58.9% vùng dự đoán là bọt khí là đúng.
Recall (R)	0.529	Mô hình phát hiện được 52.9% số vùng có bọt khí thực sự tồn tại.
mAP50	0.580	Trung bình độ chính xác ở ngưỡng IOU ≥ 0.5 khá tốt với dữ liệu thực tế.
mAP50-95	0.265	Chỉ số mAP toàn diện, đánh giá chất lượng phân biệt mô hình ở nhiều IOU.
Số ảnh kiểm thử	24	Số ảnh được dùng để đánh giá hiệu năng mô hình sau khi huấn luyện.
Tổng số đối tượng	157	Tổng số nhãn “Bubble” trong tập validation.

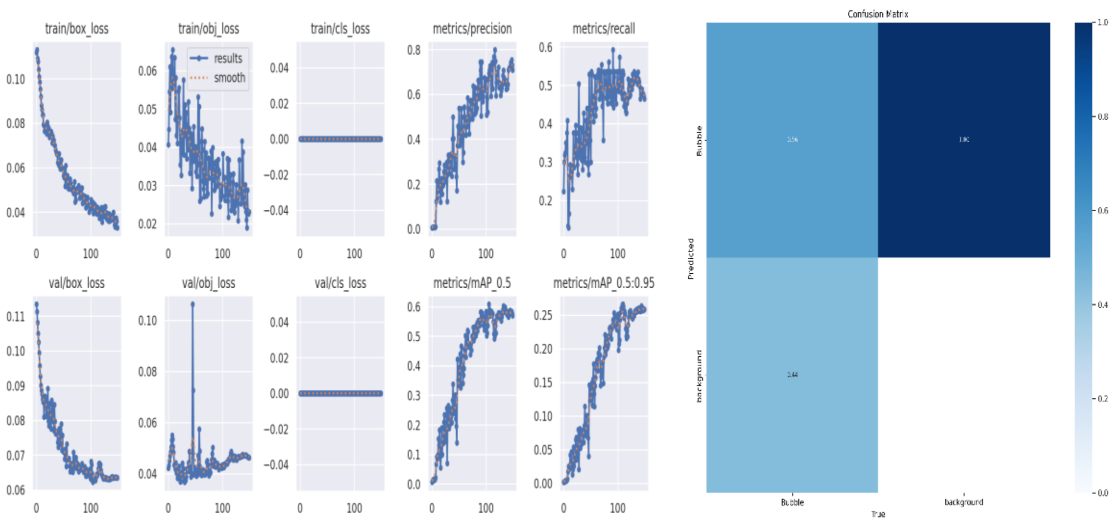


Figure 5.5 Charts of loss, precision, mAP and the confusion matrix

c) Operation results:

During the actual deployment, the bubble detection model has shown stable operation under indoor natural light conditions. The simulated and tested scenarios include both

- **Anomaly detection**

When the camera records an image that does not show any area classified as "Bubble" with a reliability exceeding the configured threshold, the system will assess the high probability that the aerator is having a problem or stopping working. In this case, an immediate warning is automatically sent to the administrator via email for timely handling.

Figure 5.6 Dispatch alerts when abnormal phenomena occur

- **Identify normal state**

In the normal operating state, the model accurately detected many air bubble regions at the air outlet from the aerator. The bounding boxes had high confidence, ranging from 0.75 to 0.90, reflecting good recognition ability under favorable observation conditions.

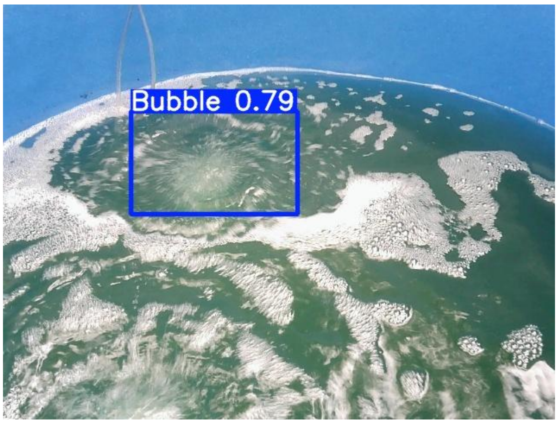


Figure 5.7. The system's accuracy based on bubble detection

d) Overall assessment

- **Advantages:**

The system operates in a fully automatic manner, eliminating the need for manual intervention during the monitoring process. It is capable of detecting aeration problems at an early stage an important factor that directly influences dissolved oxygen levels and the growth of algae. Additionally, the system is well integrated with IoT infrastructure, enabling real-time warnings and enhancing responsiveness to environmental changes.

- **Disadvantages:**

The system's accuracy may decrease when affected by interference factors such as strong shadows, murky or blurred water, and small or unevenly distributed air bubbles. It also performs poorly under low-light conditions or when dealing with reflections from the tank walls. To improve scalability, expanding the training dataset by incorporating images captured under a wider range of environmental conditions and enhancing the labeling process will contribute to increased accuracy. Furthermore, the model can be upgraded to more advanced architectures—such as YOLOv8 or EfficientDet to optimize overall detection performance.

CHAPTER 6. CONCLUSION

6.1 SUMMARY OF TOPIC

After a serious research process, practical implementation, and multiple testing, the topic "Design of smart IoT system for algae farming—Blue Carbon solution" has achieved all the initial goals. The system is completely designed, tightly integrating hardware, software, communication, and computer vision components.

The system is capable of continuously monitoring important environmental indicators such as pH, temperature, DO, and TDS; transmitting data in real time via MQTT protocol to the internal server (Raspberry Pi); storing using InfluxDB; displaying visually via Node-RED Dashboard; and combining deep learning models (YOLOv5) to analyze images and detect problems such as loss of air bubbles—early warning signs of aerator failure.

In addition to the technical system, the implementation team also deployed an experimental algae farming model, monitored it throughout the 15-day cycle, collected data, and evaluated the stability and scalability of the model. It can be affirmed that the project has successfully built a smart environmental monitoring model with high applicability in practice while demonstrating the pioneering spirit in bringing IoT and AI technology to serve the green agriculture sector—an inevitable development trend of the 21st century.

6.2 LIMITATIONS

Despite the positive results, the project still has certain limitations. The YOLOv5 deep learning model performs well under standard lighting conditions but encounters difficulties in low-light environments or when dealing with water surface reflections. Additionally, the TDS and DO sensors require manual recalibration after prolonged use, which may affect measurement accuracy over time. The system's warning mechanism currently relies on static threshold values and does not yet integrate an automatic feedback control algorithm. Moreover, the system has not been tested in outdoor or harsh environmental conditions, so its long-term operational stability has not been fully validated.

6.3 DEVELOPMENT ORIENTATION

The topic opens up a highly promising research direction with significant potential for further development in both academic and practical applications. Moving forward, the system can be expanded and improved in the following key areas:

First, the AI model used for image recognition and anomaly detection can be further optimized and upgraded. By retraining the model with a more diverse and extensive dataset—including images captured at night, under poor lighting, or with strong water surface reflections—the system's robustness and adaptability to different environmental conditions can be significantly improved. This enhancement would allow the model to maintain high accuracy and reliability across real-world deployment scenarios.

Second, the integration of additional advanced environmental sensors would significantly enrich the system's functionality. Incorporating sensors for measuring light intensity, carbon dioxide (CO_2), ammonia (NH_3), and turbidity would enable the system to evolve into a comprehensive water quality monitoring station. This would provide a more holistic view of the algae cultivation environment and enable more precise control over biological and chemical parameters, ultimately improving algae productivity and system efficiency.

Third, the implementation of smart decision-making algorithms would mark an important advancement in automation. Instead of merely issuing warnings, the system could autonomously respond to environmental changes—automatically injecting nutrients, adjusting the intensity or duration of photosynthetic lighting, or modifying aeration cycles based on real-time data analysis. This closed-loop control mechanism would enhance the system's intelligence and reduce the need for manual intervention.

Fourth, the project holds great potential for commercialization. By refining the hardware design and packaging the system into compact, modular units, it could be deployed in cooperatives, research centers, or small- to medium-scale algae farms. This would make advanced monitoring and control technology more accessible to a wider audience, supporting the spread of precision aquaculture and smart farming practices.

Finally, integrating cloud connectivity would further elevate the system's capabilities. By uploading data to platforms such as Firebase, Azure IoT Hub, or AWS IoT, it would be possible to perform large-scale analytics, enable real-time remote monitoring, and manage multiple deployment sites from a centralized dashboard. This approach not only improves operational efficiency but also supports future integration with AI-powered decision-making tools and predictive maintenance systems.

REFERENCES