INDOOR HYDROPONICS FARMING SYSTEM MONITORING VIA INTERNET OF THINGS (IoT)

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Biomedical Engineering with Honours

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

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ABSTRACT

Hydroponics is a soilless farming method that provides plants exactly what they need when they need it. This project aimed to develop a smart hydroponic monitoring system using Internet of Things (IoT) technology. The system was designed to measure important environmental parameters, including water temperature, humidity, surrounding temperature, pH value and electrical conductivity of nutrient solution, using various sensors connected to a microprocessor. The data were then displayed on a dashboard in Cayenne, enabling continuous monitoring of the growing environment of crops. Two experiments were conducted on the built prototype to determine the optimal fertilizer volume and frequency for Amaranthus tricolor (Bayam Hijau), and the results showed that 8ml of fertilizer, applied twice during a 10-day growing cycle, was the most effective. The productivity of hydroponic agriculture systems was evaluated through a meta-analysis that estimated global vegetable crop yields based on data gathered from relevant literature. Additionally, the effect of 2 criteria of the growing system on hydroponic crop yields, namely growing orientation (vertical vs. horizontal) and the condition of the growing environment (controlled environment vs. open air) were studied. Through the meta-analysis, hydroponics was found out to be more suitable for “Anise, badian, fennel & coriander”, “Chillies & peppers” and “Cucumbers & gherkins”. In terms of growing environment, controlled environment led to a higher hydroponic crop yields than open air agriculture for all the significantly affected crop categories. However, an overall trend regarding the best growing orientation could not be observed. Overall, this project provides valuable insights into the optimization of hydroponic farming for enhanced crop yields and sustainable agriculture.

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LIST OF SYMBOLS / ABBREVIATIONS

DWC	Deep Water Culture
EC	Electric conductivity
IoT	Internet of Things
NFT	Nutrient Film Technique
TDS	Total Dissolved Solids
OAA	Open Air Agriculture
CEA	Controlled Environment Agriculture
n	Number of Observations

CHAPTER 1

INTRODUCTION

1.1 Introduction

Indoor hydroponic farming systems are getting increasingly popular in Malaysia, especially in city such as Selangor and Penang. For instance, Agroz Group Sdn. Bhd. has established a 100,000 square feet indoor urban farm in Sungai Buloh, Selangor, capable of producing around 3 tons of fresh vegetables daily. This is made possible by carefully controlling the environmental conditions such as humidity, temperature and amount of lighting (Wong, 2020).

Hydroponics is an alternative farming method to the soil-based farming system. Hydroponics is a soilless farming method, sub in a growing media such as rockwool, peat moss, sawdust or even sponge to support the roots of the plants and grow them directly in nutrient-rich water. The fundamental principle of hydroponic farming is to provide plants exactly what they need when they need it. This principle can be achieved through hydroponics as it allows control and adjustment over environmental conditions like humidity, temperature and pH value, while maximizing plants' exposure to nutrients and water (Woodard, 2019). The plants will get all the needed nutrients through a nutrient solution supplied to their roots.

Agriculture makes up a large proportion of economic sector in Malaysia, contributing 7.4% to the national GDP in year 2021 (DOSM, 2021). It mainly composes of cash crops, such as rubber, palm oil, and cocoa. However, the cultivation of food crops such as fruits and vegetables are not common. Malaysia has always been dependent on imported vegetables and fruits as its own production cannot fulfil the demand of the local market. In 2020, Malaysia has imported RM5.4 billion worth of vegetables. With the negative effect brought by Covid-19 pandemic, combined with the threat of worsening soil quality as well as global climate anomalies has significantly affected Malaysia's agricultural productivity. Chiong (2022) reported that the Malaysia Food Price Index reached a 10-year high, with an increase of 27% in year 2021. Prices of choy sum have increased from RM3 per kg to RM9 per kg, a tremendously rise of 200% (Radhi, 2021). As a solution to this, it has becoming more common for commercial farmers of these crops to grow hydroponically rather than in soil, as production of hydroponics can be enhanced up to 3 times in the same amount of space as compared to traditional farming system (National Park Service, 2021). It is important for a country to be able to achieve self-sufficiency in agriculture products where the supply of food could meet the demand for growing population of the country.

There are 6 primary types of hydroponic systems, including water culture, nutrient film technique (NFT), aeroponic, Ebb and flow, drip, and wicking. While these systems share the same basic elements, they differ in the way they deliver these requirements. Indoor hydroponic farming does not require natural sunlight as sufficient amount of light can be provided by LED grow light. LED grow lights support photosynthesis of plants by either mimicking the light spectrum of the sun or offering specific wavelengths depending on the plants' need to help with the growth of indoor plants in any climate, any time of year. The LED grow lights usually combine the blue and red colour. Blue colour LED with wavelength 460nm – 470nm is extremely important for plant growth as it is important in production of chlorophyll which contributes a lot in photosynthesis process, producing in healthier plants. Red colour LED with wavelength 620nm - 700nm promotes plant growth, resulting in larger fruits (Brittany, 2022).

By implementing Internet of Things (IoT) into hydroponic farming industry, with the help of various types of sensors and interconnectivity, monitoring of every environmental factor including pH value, temperature, humidity, electrical conductivity as well as light intensity could be achieved easily. Iot is a sustainable solution which has the potential of minimizing labour and resources, saving additional fine-grained management in watering and fertilization, at the same time, ensuring the continuous production of high-quality yield. IoT helps in gathering real-time data where these data can be accessed anywhere, anytime. It boosts the crop management to the next level by offering upkeep and automatic monitoring of plants (Sean, 2021).

The productivity of hydroponic agriculture systems was evaluated through a meta-analysis that estimated global vegetable crop yields based on data gathered from relevant literature. The FAOSTAT's global average yields of conventional soil-based agriculture were used as a reference to compare the crop yields between soil-based and hydroponic farming system. It is crucial to have a piece of synthesized current information about the potential of hydroponic farming for food production as public understanding of hydroponic agriculture is relatively new compared to the conventional soil-based farming system. The study also examined the impact of two factors on hydroponic crop yields: the growing orientation (vertical vs. horizontal) and the condition of the growing environment (controlled environment vs. open air).

1.2 Importance of the Study

The importance of this study is to enhance the efficiency of crop production by developing an indoor hydroponic system with IoT, allowing for monitoring of crop growing environments wherever Wi-Fi is available. The smart farming system is equipped with various sensors, such as Total Dissolved Solids (TDS) meter to measure the electrical conductivity (EC) of the nutrient solution provided, DHT11 to measure the surrounding temperature and humidity of the plants. Various environmental conditions including light intensity, EC value, environment temperature, water temperature, humidity as well as plants' real-time conditions are constantly monitored through the system.

This system empowers farmers to visualize and observe real-time data, as well as historical graphs of the environmental parameters measured. This helps them to make informed decision in optimizing the plants' growth condition by adjusting the nutrient level, light intensity, temperature and so on. For example, if the data shows that the EC value of the hydroponic solution is out of range, the farmer can reduce the nutrient level by diluting the solution. The continuous monitoring system ensures that a stable hydroponic environment is provided to the crops, thus enhancing the quality and quantity of the crops produced as the system fully and optimally meets the nutritional needs of the plants.

Experiments were conducted on the small-scale hydroponic prototype that was developed in this project to test its functionality and performance. In addition, the experiments were carried out by adjusting the fertilizer volume and fertilizing frequency to prove the concept of how fertilization process can affect the plant growth.

The global meta-analysis conducted in this project regarding to the food production and vegetable crop yield provides solid evidence of the crop yields for hydroponic agriculture, which can contribute to improving the crop productivity, global food self-sufficiency as well as self-sustainability. By identifying the hydroponic growing systems with the highest vegetable crop yields, it can help to shape the future agriculture practices and research.

1.3 Problem Statement

After centuries of misuse and mismanagement of land, the conventional farming methods are now no longer efficient due to the problem of soil deterioration, climate change and pollution caused by chemical fertilizers and pesticides. For instance, monocropping for years can deplete soil nutrients, reduce organic matter in soil and cause significant soil fertility decline (Begum, 2021). A greener alternative method of farming – indoor hydroponic farming has become a popular option for effective food production. Growing crop using hydroponic method ensures sustainable farming and greater high-quality yields with lesser space, water, resources required.

Conventional agriculture requires a lot of manpower to maintain optimum environmental conditions for the plants to grow healthily, and it is challenging for the farmers to constantly monitor the large areas of land and the condition of all the plants. Countermeasures could not be taken immediately when there are some problems with the setup. Moreover, it is difficult to provide an ideal environment for each plant type with different growth requirements when planting multiple crops in one plot (Chandler, 2019).

However, the suitability of hydroponic systems for agriculture, which growing system has a better performance, and how this method of food production can meet rising global demand remains relatively unspecified. Therefore, there is a need to enhance public understanding of hydroponics' potential for food production to make it more popular and common worldwide and eventually reduce the global issue of food insecurity.

1.4 Aim and Objectives

This project aimed to develop a smart indoor hydroponic farming system with IoT technology to monitor the crops' condition as well as to enhance public understanding of hydroponics' potential for food production.

The study has 3 main objectives: to design an indoor hydroponic farming system with complete automated monitoring using sensors, microcontrollers and other electrical components which allows real-time monitoring of the indoor hydroponic crops; to identify the optimal fertilizer volume and frequency of Bayam Hijau by conducting experiments on the developed monitoring system; to evaluate the agronomic suitability of hydroponics and to identify the best hydroponic growing system through a literature study by collecting mean values of crop yields for various types of vegetable crops from reliable sources and analysing them.

1.5 Scope and Limitation of the Study

The scope of this study is mainly to build a prototype of hydroponic farming setup with a complete monitoring system. The implementation of IoT technology in this project employs various sensors connected to a microprocessor to measure the parameters of interest, including water temperature, humidity, surrounding temperature, EC value and so on. The data collected will then be displayed on a web application which allows continuous monitoring the crops' growing environment.

However, this study has limitations. Firstly, the RM500 budget limit provided for this project, and so, most of the electrical components used are inexpensive and merely for non-commercial use. Hence, the readings and measurements acquired from the affordable sensors are usually not that sensitive to the changes and its accuracy tends to be poor as compared to professional monitoring devices. Without sufficient level of accuracy, the data obtained through the monitoring system may not be that reliable.

Next, the prototype built is small-scale and can only fit in 8 nets of crops at one time. It may be slightly different from the large-scale farming where involves commercial agriculture for the purpose of selling. Even so, the system is still possible to be implemented onto a commercial large-scale farming with some modification needed, longer period and higher budget allocated.

Due to time constraints, only a limited number of experiments could be conducted to investigate the optimal fertilizer volume and fertilizing frequency of bayam hijau.

In the meta-analysis, a few numbers of crops such as “Pumpkins, squash and gourds” and “Beans” were excluded from the analysis due to insufficient data, which may have limited the completeness of this study. This might affect the completeness of this study as there are only few vegetable crop categories being involved and compared in the investigation of the potential differences among the growing systems.

1.6 Contribution of Study

Firstly, this project has demonstrated the feasibility of implementing a smart hydroponic monitoring system that uses IoT technology. The system allows continuous monitoring of the growing environment of hydroponic crops through various sensors and a web application, which can help farmers to optimize their crop yields.

Secondly, the study has identified the optimal fertilizer volume and frequency for the growth of Amaranthus tricolor (Bayam Hijau), which is an important vegetable crop in many parts of the world. This information can be useful for hydroponic farmers to maximize their yields and minimize the use of fertilizers.

Lastly, the meta-analysis conducted in the study has provided insights into the agricultural productivity of hydroponic systems, which can help in the development of sustainable and efficient agriculture practices. Other than that, the study has investigated how the growing orientation and environment affect the hydroponic yields, which can provide insightful information for farmers in selecting the best growing conditions for their crops. Overall, the study has made important contributions to the field of agriculture and technology and can be used as a basis for further research in this area.

1.7 Outline of the Report

The report comprehensively discusses the project's background, significance, objectives, problem statement, scope, and limitations, as well as its contribution to the field of hydroponics. Relevant literature on hydroponics was thoroughly researched and analyzed. The report also details the methodology and work plan used to conduct the project. The obtained results are presented and discussed in-depth, including the experiments conducted to determine the optimal fertilizer volume and frequency for Bayam Hijau in the developed monitoring system. Finally, the report concludes with recommendations for future studies to further enhance the hydroponic farming system.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the types of hydroponic farming were studied. There are 6 primary types of hydroponic systems, including water culture, nutrient film technique (NFT), aeroponic, Ebb and flow, drip, and wicking. Also, the pros and cons of each farming technique have been discussed. The environmental parameters that might affect the plant growth such as electrical conductivity (EC) value of the nutrient solution, surrounding temperature, humidity, pH level, water temperature, and light intensity were discussed. Lastly, various IoT platforms including Cayenne, Blynk, Google Cloud and so on, were compared and reviewed based on their level of convenience, pricing, and efficiency. With this literature review, the most suitable hydroponic farming system and IoT platform for this project were selected, with the purpose of remotely monitoring the EC value and temperature of nutrient solution and atmospheric temperature and humidity in order to enhance crop quality as well as productivity while keeping minimal human intervention.

2.2 Types of Hydroponic Farming

Hydroponic system is the modern farming technique where the crops are planted without soil and nutrient are supplied to the crops via mineral fertiliser solutions in a nutrient solvent. The hydroponic solution is continuously supplied to the roots of the plants and the plants will absorb the organic nutrients as needed. It serves as an alternative practice to the traditional farming method especially in urban areas as it is able to produce higher yield and quality crop within a shorter period and lesser space is needed. The conventional farming practice is slowly replaced by hydroponic system due to the difficulties encountered in ploughing, irrigating, weeding, soil erosion, as well as soil-based crops diseases such as damping-off and root rot (Dutta et al., 2021). The 5 major types of hydroponic systems will be discussed in this chapter.

2.2.1 Nutrient Film Technique (NFT)

NFT uses a water pump to drain the roots of crops with a non-stop shallow stream of nutrient solution, while the unused nutrient solution is being regularly recycled within the closed system as shown in Figure 2.1. The inclined grow tray is the one of the characteristics of NFT system, which serves the purpose of flowing the water down towards the pipe with the aid of gravity. Besides, the shallow flow of solution ensures that the roots can absorb nutrient solution but are not completely soaked, at the same time, the roots can take in oxygen as they are suspended in the air. As the roots are suspended in little or even no growing medium, hence, without sufficient support, NFT can only work on small and light plants such as lettuce and parsley (D'anna, 2022). Table 2.1 discussed about the advantages and disadvantages of NFT system.

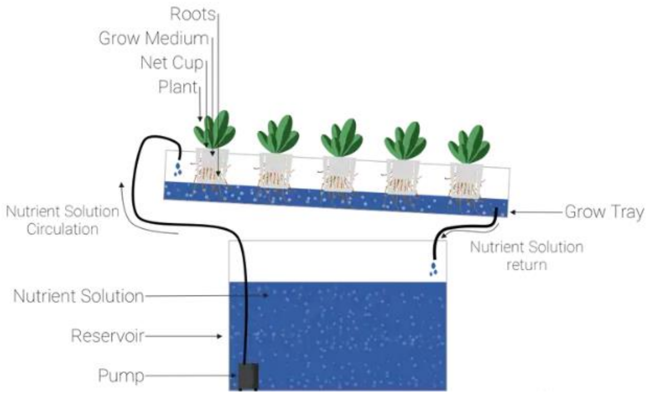

Figure 2.1 NFT Farming Method (Gutsche, 2021)

Table 2.1 Advantages and Disadvantages of NFT System (Gutsche, 2021)

Advantages of NFT	Disadvantages of NFT
• Efficient consumption of water and nutrient	• Nutrient solution has to be circulated permanently
• Easy to check on the crops' condition as the roots can be assessed easily	• Not suitable for large and heavy plants due to insufficient support
• Lesser mineral deposition due to the continuous flow of solution	• The flow can be clogged by the roots
• Easy and simple setup	

• Little or even no growing medium is required	• High level of direct sunlight can heat up the grow tray and damage the roots

2.2.2 Ebb and Flow

It is also known as flood and drain where the root systems of the crops are periodically drained by nutrient-rich solution as shown in Figure 2.2. This system involves a timer to control the time for every water pumping cycle. The solution is pumped to the grow tray until it reaches the water limit to fulfil the crops' nutritional need. When the timer goes off, the pump is turned off and the solutions flow back into the reservoir. The period between the timer goes on and off create a moist yet well aerated environment to the root systems (D'anna, 2021). Table 2.2 discussed about the advantages and disadvantages of Ebb and Flow system.

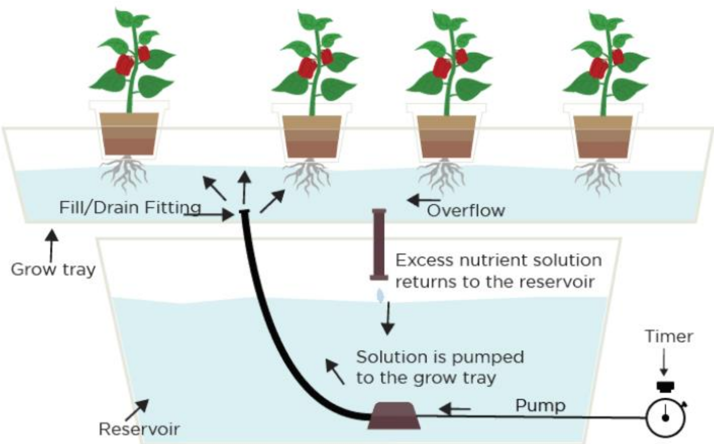

Figure 2.2 Ebb and Flow Hydroponic System (Trees.com, 2022)

Table 2.2 Advantages and Disadvantages of Ebb and Flow System (D'anna, 2021)

Advantages of Ebb and Flow	**Disadvantages of Ebb and Flow**
• Easy to set up and use • Inexpensive • Ensure the crops has taken up nutrients as needed	• Depend on power supply to function • Can be contaminated by pathogens in the reservoir and

• High versatility as it works on a variety of plants ranging from fruits to leafy vegetables	grow tray due to the stagnated solution during the "ebb" stage • Less oxygen can be obtained by the root systems

2.2.3 Aeroponics

Aeroponics is a hydroponic farming method that suspend the plants in the air and several mist nozzles are positioned below them to spray the nutrient-rich solution as a vapour directly on the root systems as shown in Figure 2.3. The mist is formed by shaking the solution with high frequency sound waves created from ultrasonic technology. The excess solution will fall and accumulate into the reservoir below, then, the solution will be recycled again and again to be sprayed onto the root systems. With the roots exposed to the air, they are able to obtain as much oxygen as they need. Surplus oxygen accelerates the absorption of nutrient at the root surface (Jefy, 2021). Table 2.3 describes its pros and cons.

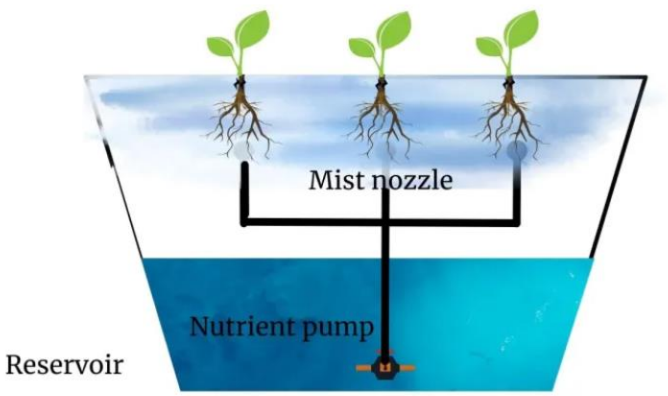

Figure 2.3 Aeroponics System (Jefy, 2021)

Table 2.3 Advantages and Disadvantages of Aeroponics (Barth, 2018)

Advantages of Aeroponics	Disadvantages of Aeroponics
• Maximize obtainability of oxygen • Higher nutrient absorption rate • Less prone to pathogens, pests and diseases	• Highly sensitive to environmental conditions • Expensive set up • Require continuous monitoring • Require proper knowledge and training before starting up

• The crops can be moved and replaced with new one easily	• Require regular maintenance on the nozzles as they can be clogged up easily by the mineral deposits in the solution • Highly depend on power supply to function

2.2.4 Wicking System

Wicking system involves a wick, which is a soft fabric string, to take in nutrients and water from the solution to the plants, instead of submerging the root systems directly into the nutrient solution as shown in Figure 2.4. One end of the wick is inserted into the grow medium near the root systems, and the other end is placed into a reservoir that contains the nutrient solution. The wick will draw up the nutrient solution based on capillary action, until the medium is moist. The wick will absorb water again once the medium dries out. However, this system does not work well for the water-hungry plants such as tomato as it is unable to provide sufficient water to the crops. Wicking system is a passive hydroponic method as it functions without the need of any electricity, pumps, motor, or other moving elements (D’anna, 2022). Table 2.4 below discussed about its advantages and disadvantages.

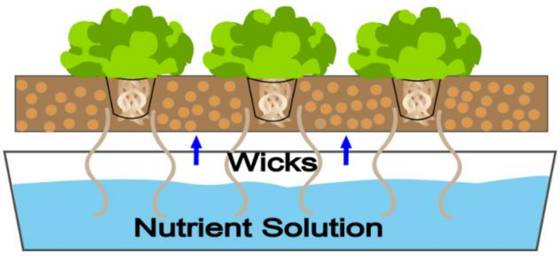

Figure 2.4 Wicking System (Courtney, n.d.)

Table 2.4 Advantages and Disadvantages of Wicking System (Sargent, 2018)

Advantages of Wicking System	Disadvantages of Wicking System
• Affordable • Low maintenance cost • Does not depend on power supply to work	• The crops have to be flushed out with clean water regularly to avoid a buildup of mineral salts in the growing medium’

	• Does not work well in larger and thirsty plants

2.2.5 Deep Water Culture (DWC) System

DWC is a hydroponic technique that completely submerges the root systems in a nutrient-rich and high oxidized solution as shown in Figure 2.5. It requires a large reservoir to store large quantities of water that is sufficient to totally submerge the roots. The larger the quantities of water available in the reservoir, the higher the stability of the crops. Air pump is used to provide supplemental aeration to the root systems and to balance the oxygen level in the solution since the roots are submerged in water 24 hours in a day (Hall, 2022). Table 2.5 discussed about the advantages and disadvantages of DWC system.

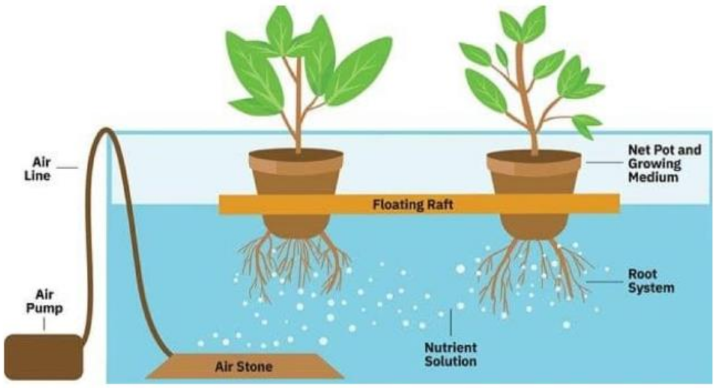

Figure 2.5 Deep Water Culture (DWC) System (Wortrich, 2022)

Table 2.5 Advantages and Disadvantages of DWC (Espiritu, 2021)

Advantages of DWC	Disadvantages of DWC
• Low start-up and maintenance cost • Simple setup • Accelerated growth of plants	• Difficult to maintain a consistent water temperature as the water is not circulated regularly • Has to constantly oxygenate the water • The pH level and oxygen level tend to fluctuate when the number of crops is small

2.3 Growth Parameter

Internet of Things (IoT), various sensors and microprocessor are implemented in hydroponic system to remotely monitor electrical conductivity (EC) value of the nutrient solution, surrounding temperature, humidity, pH level, water temperature, and light intensity accurately, keeping minimum human intervention while optimizing the plant growth parameter.

2.3.1 Water Temperature

When the water temperature increases, the plants' metabolic rate increases, and so, the plants require more oxygen. Contrarily, the amount of dissolved oxygen in the nutrient solution decreases in warmer water. When the plant is not able to access to sufficient amount of oxygen from the water, its ability to absorb nutrient will decrease significantly. Also, warmer water has a negative side effect of being a breeding ground for root borne insects, fungus and bacteria which are deleterious to crops.

On the other hand, when the water temperature is too low, it forces the plants to shut down and absorb less nutrient, leading to lower growth rate. Therefore, the water temperature should be maintained within an optimum range where the plants reach a compromise between metabolism rate and usage of oxygen. Usually, for commercial plants, the ideal water temperature is between 15°C to 30°C (Bartok, 2018).

2.3.2 Surrounding Temperature

Surrounding temperature has direct impact on the humidity. Excessive high temperature causes the plants to lose water quickly via evaporation, while low temperature causes the nutrient absorption rate to decrease. Also, photosynthesis rate is affected by surrounding temperature. When the temperature increases, the enzyme Rubisco started to denature and its activation rate declines, causing inefficient photosynthesis. While at lower temperature, the photosynthesis rate is limited by the number of collisions between substrate and the enzyme (Markings, 2018).

2.3.3 Surrounding Humidity

Optimum humidity level keeps the plants in a moist and healthy growing environment. Excess humidity affects the absorption of nutrient as the stomata in the leaves will detect that the surrounding air is moist, and it will stop taking up water through the roots even when the plant itself does not absorb sufficient water yet, eventually leads to dehydration of plants. Also, excessive high humidity environment is favourable by the harmful fungus (Brookes, 2016).

2.3.4 Electrical Conductivity (EC) of Nutrient Solution

EC value in hydroponic measures the level of dissolved salts in the hydroponic solution. EC indicates ability of the solution to conduct electric current due to the presence of mineral salts. The nutrient concentration in the solution plays a critical role in maximizing the plant growth and production yield. It is usually measured in in milli Siemen (mS) or Parts per Million (PPM). High EC level can lead to ion toxicity and nutrient absorption blockage as a result of the increased osmotic pressure. Conversely, low EC value can affect plant growth and health due to nutrient defficiency. The uptake rate of water is directly proportional to the EC value (Cook, 2020).

The EC value is varied according to the stages of plant growth. The EC value can be adjusted to optimum range by diluting the solution with water or concentrating it with nutrient solution. The solution is said to be balanced if the EC value remains constant for a specific period, where the crop is taking up as much water as it is nutrient. The decline in EC value shows that the plant needs more nutrient consumption than water, in other word, underfeeding. As a solution to this, higher concentration of nutrient solution should be added to the plants. If the EC level increases, it indicates that the plant is overfed by nutrients, leading to brown leaf tips due to nutrient burn. Water should be added to dilute the hydroponic solution (Cooper, 2022).

2.3.5 Potential of Hydrogen (pH) Value

pH value of a nutrient solution in hydroponics defines its level of acidity or alkalinity. Based on Figure 2.6, the pH scale ranges from 0 to 14, 7 is the pH-neutral point, 0 being the most acidic and 14 the most alkaline. It will affect the availability of particular nutrients for plants absorption (Lynne, 2019). If the solution is too acidic, the crops will absorb micronutrients such as iron and zinc in toxic levels while macronutrients such as potassium and phosphorus are lacking. Conversely, if the solution is too alkaline, absorption of micronutrients decreases (Cook, 2021).

Figure 2.6 pH Scale (Cook, 2020)

The change in pH value will affect the photosynthesis rate as well. pH fluctuates as the crops constantly take up acidic nutrients from the solution, causing the solution to become more alkaline. Therefore, potassium hydroxide and phosphoric acid are usually used to increase or decrease the pH value when it is out of optimum range. For different species of plants, the optimum pH value might be slightly different, but 5.5 to 6.5 is suitable for most of the crops in hydroponic system (Mehboob et al., 2019). If the pH value is too low, for instance 2, it shows that the root systems are exposed to strong acidity solution, resulting in damaging the roots.

2.3.6 Light Intensity

LED grow light is usually used as a substituent to the sunlight in indoor hydroponic farming, which serves the purpose of maintaining plant’s life cycle in the absence of natural sunlight. Generally, outdoor farming requires about 4 to 8 hours of direct sunlight per day, and 4 to 10 hours of indirect sunlight, and 10 to 12 hours of darkness to redistribute water and nutrients to every part of plant, depends on the species of crop. For example, to grow lettuce indoor requires up to 18 hours of sunlight per day since it is a long-day plant (EdenGreen, 2021). The benefit of using grow light is that it offers different ranges of wavelengths to imitate natural sunlight condition. With that, the indoor plants are able to receive optimal amount of sunlight without being dependent on the climate (Dunklee, n.d.).

The light wavelength within 400nm to 700nm is known as photosynthetically active radiation (PAR), where photosynthetic organisms are able to be used in the photosynthesis process to generate glucose for survival. Therefore, LED grow light which combines blue and red light is most commonly used. Blue light with wavelength 400nm – 500nm helps to increase the quality of leafy green plans, while red light with 600nm – 700nm wavelength promotes stem development and overall plant growth (EdenGreen, 2021).

2.4 Internet of Things (IoT) Platform

An IoT platform serves as a connection between electronic sensors and data networks. It is implemented into agricultural industry to offer automatically data collection from sensors and camera. Then, the data will be uploaded to cloud for storage as well as to provide an insight into the collected data in the backend application. According to Vasisht *et al.* (2017), the International Food Policy Research Institute has stated that the use of data-driven techniques can lead to an increase in farm productivity by approximately 67% by the year 2050. Additionally, these techniques can help reduce agricultural losses.

IoT platform is a set of components that allows organization to spread out the applications, develop connectivity, remotely gather data, and execute management of sensor. IoT platform creates a reliable connection between various devices, to collect, record, analyze and monitor data gathered by the connected devices and assets, while ensuring an uninterrupted flow of communication between the components (McClelland, 2017). With that, organization can have a better understanding on consumers' requirements and thoughts.

A desirable IoT platform must be able to collect data and deliver services continuously with minimal downtime. Its capacity should be capable to support various sensors and devices with varying requirements, ranging from water temperature sensor that transfer few bytes of data to ESP32 cam that send up to kilobytes of photos. Also, an IoT platform should be able to upload real time data to the cloud without any interruption. Long term data analytics is required in order to involve several farming systems such as farming practice advisory, crop yield predicting, seeding suggestions and crop cycle forecasting. Furthermore, with the latest sensor data, the AI agricultural application could provide suggestions on improving the farming method and yield production. If the data update is delayed, gaps in historical data can cause the applications to make inappropriate advice and decision, which consequently leads to poor user experience (Vasisht et al., 2017). Several popular IoT platforms including Blynk, Google Cloud, Open Remote and ThingSpeak will be discussed in this chapter.

2.4.1 Arduino IoT Cloud

Arduino IoT Cloud is a support application that helps users in building connected hardware devices in a secure, quick, and most importantly, easy way. Users are allowed to connect multiple devices to each other, and this platform allows them to exchange real-time data. Users can monitor and visualize the data collected from anywhere in the dashboard. The data stored in the cloud can be shared with other people around the world (Söderby, 2022).

Moreover, Arduino IoT Cloud has a scheduler feature, which allows users to schedule jobs to be turned on or off for a specific amount of duration. It is convenient to use as it has an online library where users do not have to install the desired libraries one by one. The latest feature available in Arduino Cloud is the OTA (over-the-air) feature. It allows users to upload code wirelessly to the devices not connected to the computer via a USB, as long as a compatible board is connected to a Wi-Fi network and configured to work with OTA (Garcia, 2022). Figure 2.7 shows the example of dashboard in Arduino IoT Cloud.

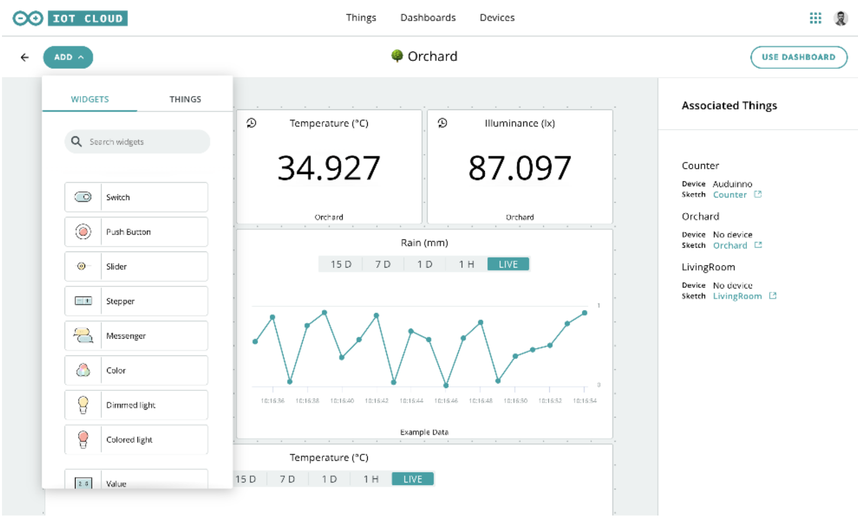

Figure 2.7 Example of Dashboard in Arduino IoT Cloud (Arduino, 2020)

2.4.2 Cayenne

Cayenne is a drag-and-drop IoT platform which developed by myDevices. It stops supporting mobile application since year 2020. Now, users can customize their online website dashboard to remotely visualize data, monitor and control the connected hardware devices such as ESP32, Arduino and others. Besides, it consists of robust scheduling features, an integrated rules engine for triggers and threshold alerts, and customized tools to visualize and analyze real-time and historical data. Figure 2.8 shows the example of dashboard in Cayenne.

Figure 2.8 Example of Dashboard in Cayenne (Cayenne, n.d.)

2.4.3 Blynk

Blynk offers the no-code method to design and build an IoT application that supports both Android and iOS since year 2014, makes it a popular choice for mobile app editor. Commonly, Blynk is used to keep track and display real-time data on a dashboard, which can be easily assessed by any smart widgets. Blynk helps to manage everything, from basic cross-platform user registrations to complicated device provisioning, sensor data analytics, as well as AI machine learning. It is an open-source tool that can compatibly work with various types of microcontrollers including Arduino, ESP32, and RasberryPi over the Internet.

According to Figure 2.9, Blynk consists of 3 systems, the Blynk mobile app to visualize and manage data on smart devices, Blynk server serves as a cloud service that ensure smooth communication between widgets and things, and Blynk libraries to enable data collected from a sensor to be displayed on a mobile application in a convenient method (Serikul, Nakpong and Nakjuatong, 2018). Figure 2.10 shows the example of dashboard in Blynk.

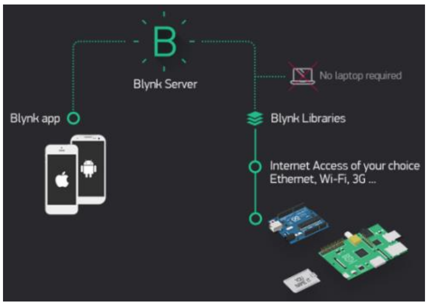

Figure 2.9 Blynk Working Diagram (Serikul, Nakpong and Nakjuatong, 2018)

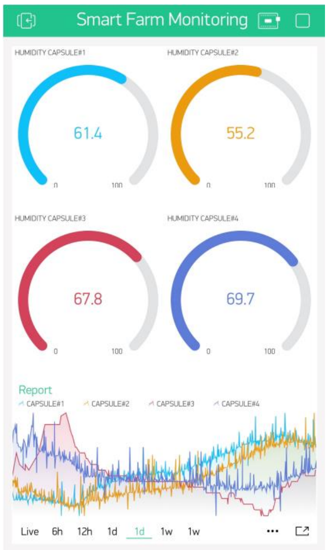

Figure 2.10 Example of Dashboard in Blynk Mobile App (Serikul, Nakpong and Nakjuatong, 2018)

2.4.4 Google Cloud

Google Cloud offers high security to protect the data as it is equipped with a multi-layered secure infrastructure. It has an end-to-end platform for IoT solutions which allows organization to connect, record and monitor huge amount of IoT data easily. Since Google is powerful and globally accessible, Google Cloud can help to make informed decisions at global scale with Google Cloud data analytics services. However, the pricing is quite expensive, starts from USD 1758 (= MYR 7835.41) (Rana, 2022). Figure 2.11 shows the example of dashboard in Google Cloud.

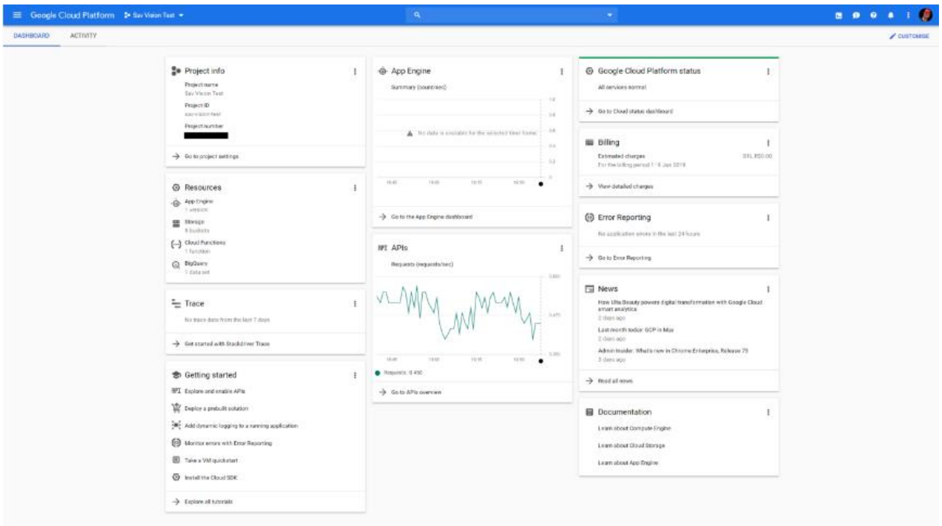

Figure 2.11 Example of Dashboard in Google Cloud (Terracciano, 2019)

2.5 Summary

The main types of hydroponic farming method were studied. The environmental parameters that might affect the plant growth such as electrical conductivity (EC) value of the nutrient solution, surrounding temperature, humidity, pH level, water temperature, and light intensity. Lastly, various IoT platforms including Cayenne, Blynk, Google Cloud and so on, were compared and reviewed based on their level of convenience, performance and efficiency.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

This project comprises of 3 main parts: building the hydroponic prototype with IoT platform; setting up experiments to investigate the optimal fertilizer volume and fertilizing frequency; conducting a global meta-analysis to review the agronomic suitability of hydroponics and identifying the growing systems with higher crop yields.

An open loop control system was developed to continuously monitoring and recording various parameters of interest such as water temperature, EC and pH level of the nutrient solution. These parameters were then sent to the ESP32 microcontroller and displayed on the IoT platform, Cayenne. Camera system was implemented to remotely monitor the plants' condition by sending a request of a new photo to the created Telegram bot.

Experiments were designed by adjusting the fertilizer volume from 4ml, 6ml to 8ml; and the fertilizing frequency from 1, 2 to 3 times in a 10-day growing cycle. The heights of the bayam hijau crops were measured and recorded at the end of experiment to identify the optimum fertilizer volume and fertilizing frequency for bayam hijau.

The vegetable crop yields of hydroponic agriculture were globally analyzed in this meta-analysis by estimating the average crop yields for different types of vegetables grown using hydroponic systems.

3.2 Block Diagram

The block diagrams in Figure 3.1 and Figure 3.2 show the entire process flow of the designed hydroponic monitoring system. The project consists of 2 system separately, a microcontroller system that connects the sensors to the ESP32, and a camera system that connect ESP32-Cam to a created Telegram bot. In the microcontroller system, the real-time parameters are continuously measured by the respective sensors and sent to ESP32. Then, the data will be sent to IoT platform and cloud interface, which allows users to visualize the recorded data on either website dashboard or on mobile application as well as to conduct data analysis. In the camera system, ESP32-Cam interact with the Telegram bot and allows user to request new photo anytime, anywhere, by sending specific commands to the Telegram bot.

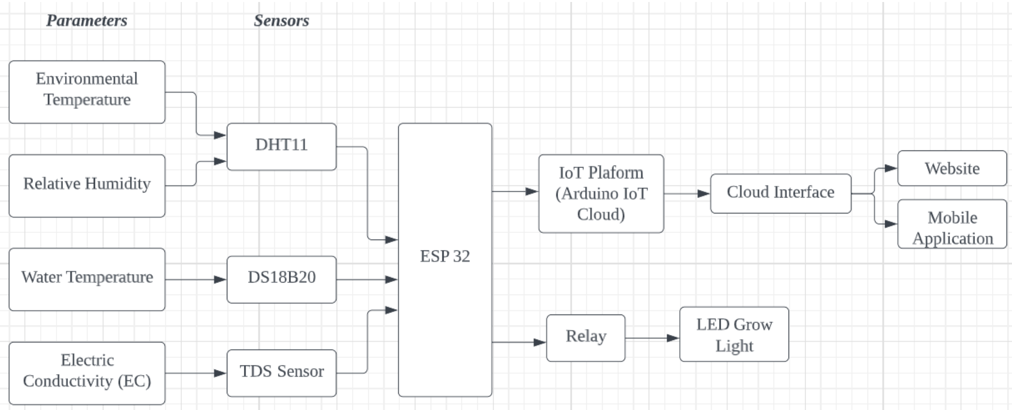

Figure 3.1 Block Diagram of IoT Hydroponic Microcontroller System

Figure 3.2 Block Diagram of the Camera System

3.3 Circuit Design

The circuit design of this project was divided into 2 parts. Firstly, the sensor system that were connected to a microcontroller ESP32, and the ESP32 was then connected to the IoT platform. DHT11, to measure environmental temperature and humidity; DS18B20, to measure water temperature; TDS sensor, to detect the electric conductivity of the nutrient solution. These sensors will detect the parameters and send the real-time data to the Arduino IoT Cloud platform to be displayed on the dashboard. With that, users could continuously visualize the growth parameter of the plants anywhere, anytime. Other than that, a 5V active low relay was connected to ESP32 to control the on and off of grow light. While on the IoT platform, the LED grow light can be remotely scheduled to turn on and off for a certain duration.

The second part was the camera system where the ESP32-Cam interacts with the Telegram bot to allow users to request a new photo from the ESP32-Cam anywhere, anytime, as long as there is internet connected. With that, the real time condition of plants can be monitored and if there is any problem, farmers are able to solve it timely.

3.3.1 DHT11 Temperature & Humidity Sensor

The DHT11 comprises a temperature and humidity sensor module that generates a calibrated digital output signal. It provides fast response, high reliability, and outstanding long-term stability. The device consists of two parts: a resistive-type humidity sensor and a thermistor. It interfaces with an advanced 8-bit microcontroller. It has 3 pins, pin 1 was connected to 5V, pin 2 to D23 in ESP32, pin 3 to GND as shown in Figure 3.3. The specification of the DHT11 is shown below:

- Humidity Range : 20 - 80% Relative Humidity
- Humidity Accuracy : ± 5% RH
- Temperature Range : 0-50 °C
- Temperature Accuracy : ± 2% °C
- Operating Voltage : 3V to 5.5V
- Sampling Frequency : 1Hz

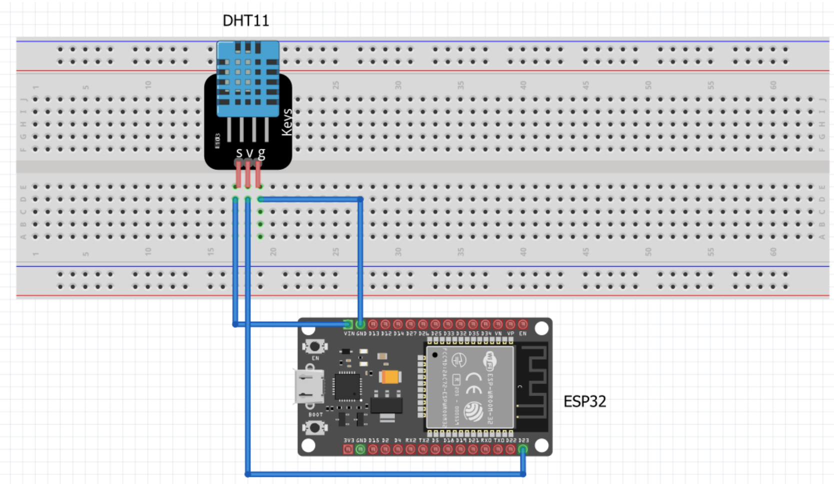

Figure 3.3 Circuit Diagram of DHT11 Sensor Connected to ESP32

3.3.2 DS18B20 Sensor

DS18B20 is a 1-Wire interface Temperature sensor that measures the water temperature through a sealed digital temperature probe. The unique 1-Wire® Interface requires only one data line for two-way communication with a microcontroller. It provides 9 to 12-bit temperature readings. It has 3 strips, black strip was connected to GND, yellow strip to D22 in ESP32, red strip to 5V. A 4.7k pull-up resistor was needed between the data (yellow strip) and power pin (red strip) to ensure the stability of data transfer as shown in Figure 3.4. The specification of the DS18B20 sensor is shown below:

- Operating Voltage : 3.0V - 5.5V
- Temperature Range : -55°C to 125°C
- Temperature Accuracy : ± 0.5°C from -10°C to 85°C

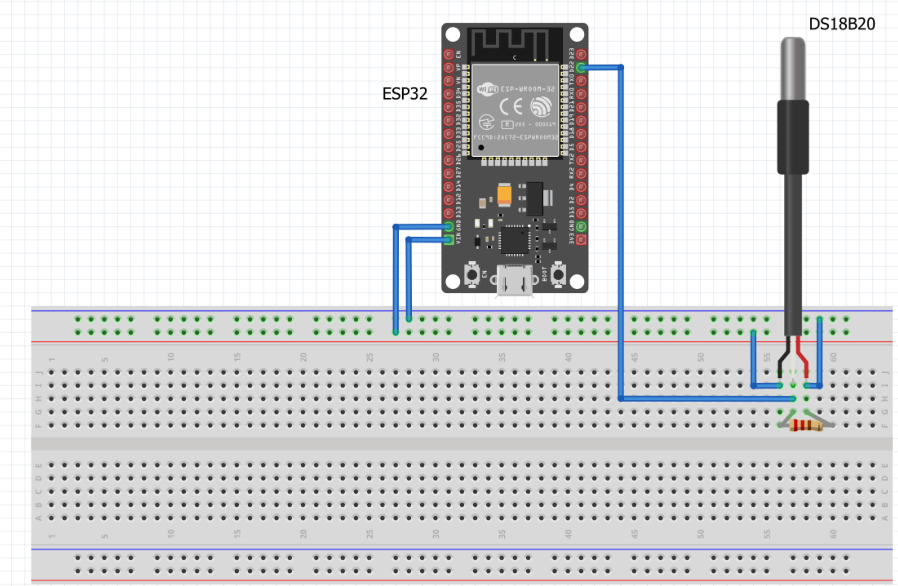

Figure 3.4 Circuit Diagram of DS18B20 Sensor Connected to ESP32

3.3.3 Total Dissolved Solids (TDS) Sensor

TDS is a measure of the amount of soluble substances present in one liter of water. In hydroponics, a TDS sensor is used to measure the electric conductivity (EC) of the nutrient solution. High EC values indicate a high concentration of dissolved solids, which can carry electric charges. To prevent probe polarization and prolong the life of the waterproof probe, an AC signal is used as the excitation source. This also helps to increase the stability of the output signal. The specification of the TDS sensor is shown below:

- Input Voltage : DC 3.3V to 5.5V
- Output Voltage : 0 to 2.3V
- Working Current : 3 to 6mA
- TDS Measurement Range : 0 to 1000ppm
- TDS Measurement Accuracy : ± 10% F.S. (25 ℃)

TDS sensor has 3 wires, power wire in red colour, ground wire in black colour and data wire in yellow wire, and they were connected to Vin, GND and pin 2 in ESP32, respectively, as shown in Figure 3.5.

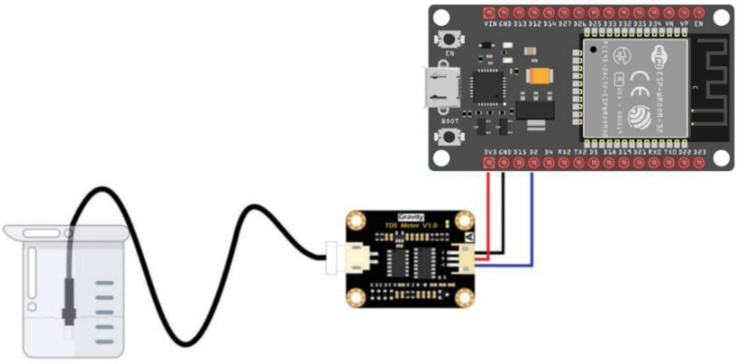

Figure 3.5 Circuit Diagram of TDS Sensor Connected to ESP32

3.3.4 pH Sensor

pH sensor was used in this project to measure acidity or alkalinity of the nutrient solution on the scale of 0 – 14, by measuring the concentration of hydrogen ion in the solution. pH value of 0 indicates extremely acidic, pH 7 for neutral, pH 14 for extremely alkalinity. It was connected to ESP32 as shown in Figure.

- Input Voltage : 3.3~5.5V
- Output Voltage : 0~3.0V
- Detection Range : 0~14
- Measurement Accuracy : ±0.1@25℃

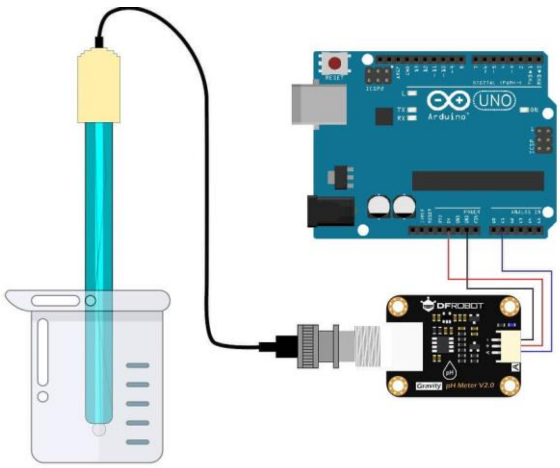

Figure 3.6 Circuit Diagram of pH Sensor Connected to ESP32

3.3.5 LED Grow Light

A full spectrum plant lamp which consists of 169 LEDs was used to boost the plant growth. The grow light was connected to ESP32 through an active low relay which acts as a switch that controls the opening and closing of the circuit contacts of an electronic circuit. In simpler words, when the state of the relay is set to “Low”, the light is turned on, and vice versa. The positive terminal of the grow light is connected to “Normally Open” in relay, where it defaults in the open position, while the negative terminal is connected to GND as shown in Figure 3.7. The specification of the LED grow light is shown below:

- Input voltage : AC 85V - 265V
- Frequency range : 50Hz - 60Hz
- Colour : (SMD2835) R + B / 165 + 60
- LED wavelength : Red 620-660nm, Blue 460-470nm

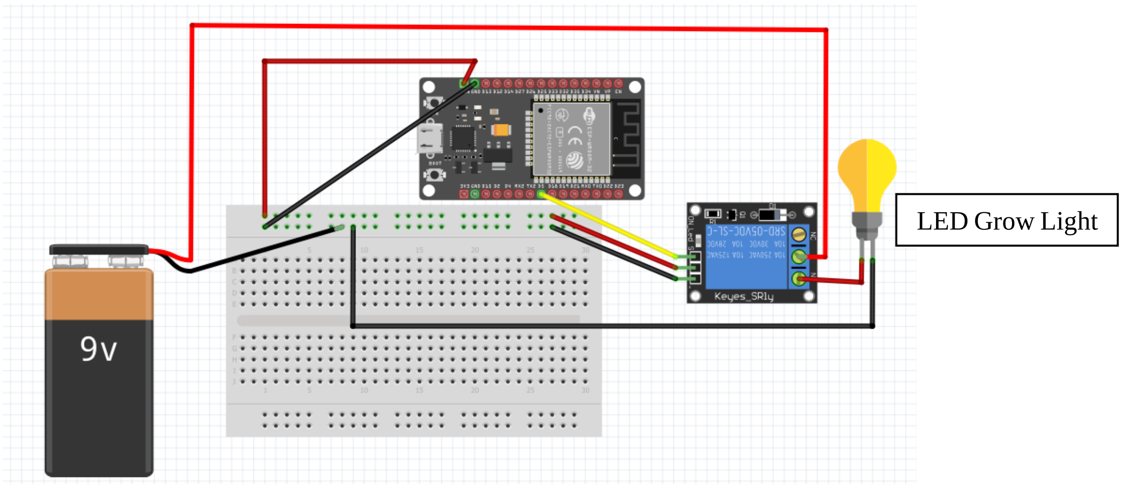

Figure 3.7 Circuit Diagram of LED Grow Light Connected to ESP32 via Relay

3.3.6 Completed Circuit Design

In the entire circuit as shown in Figure 3.8, there are 4 sensors (input) and 1 LED grow light (output) connected to ESP32 (microcontroller). Each device is connected to the pins on ESP32 as shown below:

Table 3.1 Devices Connected to ESP32

Devices	Pins	ESP32
DHT11	Vcc	Vin
	GND	GND

	Data	23
	Vdd	Vin
DS18B20	GND	GND
	Data	22
	Vcc	Vin
TDS Sensor	GND	GND
	Data	2
	Vcc	Vin
pH Sensor	GND	GND
	Data	36
	Vcc	Vin
Relay	GND	GND
	IN2	5

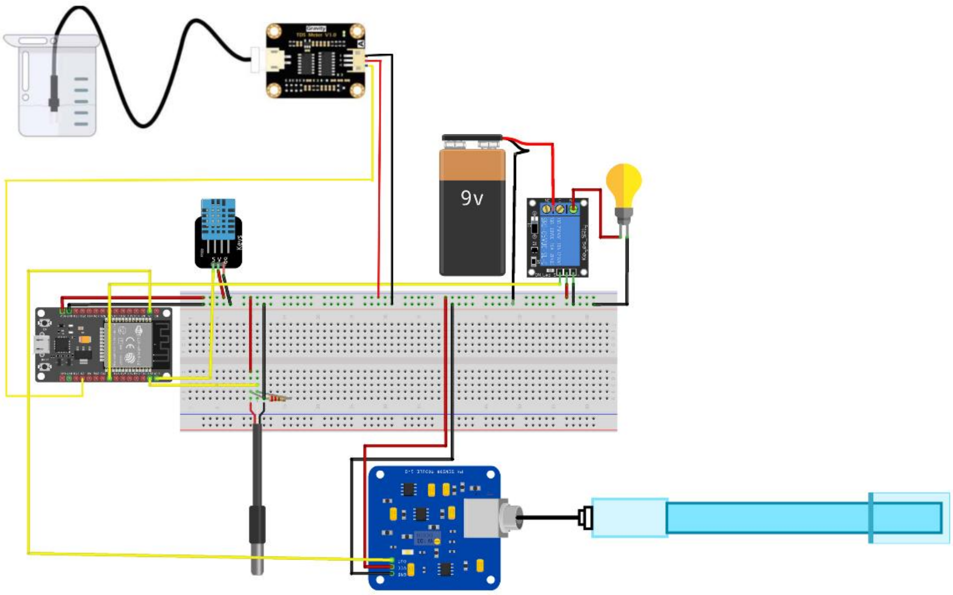

Figure 3.8 Complete Circuit Diagram with 4 Sensors and 1 LED Grow Light

3.4 IoT Platform: Cayenne

Cayenne was employed as a support software that connect various hardware devices, to collect, record, and monitor data, while ensuring an uninterrupted flow of communication between the components. The data collected by the sensors will be sent to ESP32, then timely recorded on the IoT platform and displayed on the dashboard. The dashboard was designed to easily monitor and remotely control the microcontroller from a web interface. It consists of several widgets that are linked with the cloud variables. For example, a switch to turn on or off the LED grow light, a gauge that displays water temperature, or even a line graph that shows data over time can be set up. Besides, Cayenne has a scheduler feature, which allows us to schedule jobs to be turned on or off for a specific amount of duration (seconds, minutes, hours).

3.5 Camera System

ESP32-Cam was used in the camera system due to its affordable price, small size, low power consumption and it is easy to use. ESP32-Cam comes with an OV2640 camera with a built-in flash and provides onboard TF card slot to store media files. The device is capable of supporting Wi-Fi video monitoring and Wi-Fi image upload, making it suitable for use with a telegram bot to remotely capture plant photos. Additionally, the device offers multiple sleep modes, including a deep sleep mode that can operate at a current as low as 6mA.

A Telegram bot was created to interact with the ESP32-Cam. A new photo can be requested by sending a particular message via the Telegram account from anywhere, anytime. When the message “/photo” is sent to the ESP32-Cam bot, the ESP32-Cam receives the message, takes a new photo and the photo will be sent to the telegram bot. With that, users can receive and view the photo in their Telegram account. Other than that, the message “/flash” is sent to toggle the flashlight of ESP32-Cam. Therefore, ESP32-Cam can be used to monitor the plant condition, even when the surrounding is dark.

3.6 Mechanical Design

A basic hydroponic setup was designed. A large transparent container box with dimension $559mm \times 369mm \times 330mm$ was used to carry the hydroponic tray that can grow 8 plants, together with the circuit, ESP32-Cam as well as the LED grow light. The transparent box was selected to ensure that the sunlight would not be blocked, while 2 racks were designed on top of the tray to hold the grow light right above the plants. Also, the big container does not have cover on it to ensure sufficient oxygen supply to the crops. As for the ESP32-Cam, it was placed on the corner of the container box where it can capture the plants without any obstruction.

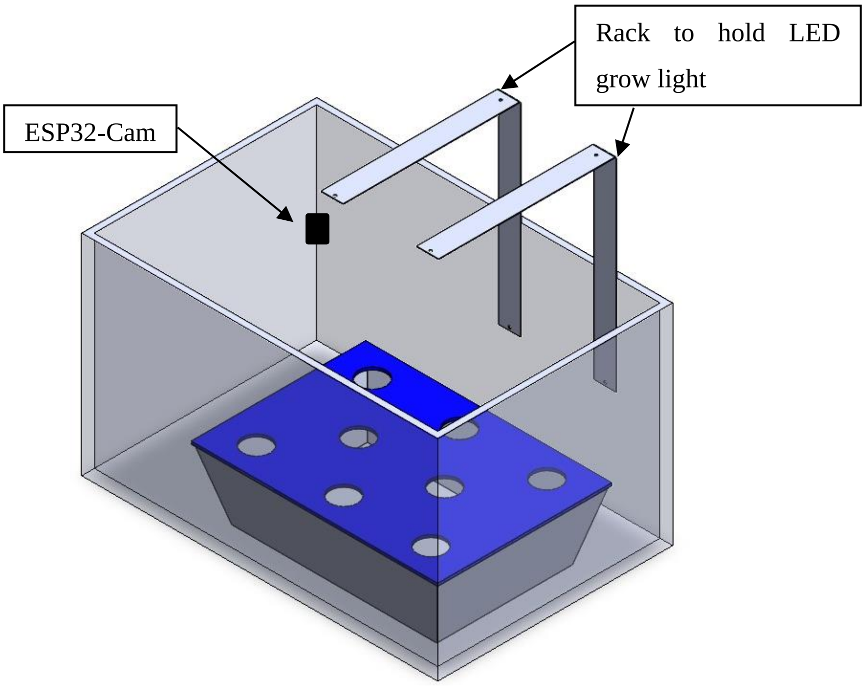

Figure 3.9 Mechanical Design for this Project

3.7 Experiments Set Up

In this study, 2 experiments were conducted to investigate the effect of fertilizer volume and frequency on the growth of Amaranthus tricolor (Bayam Hijau). In the first experiment, the number of seeds (5), growing period (10 days), and fertilizing frequency (once per growth cycle) were kept constant, while the fertilizer volume was modified from 4ml, 6ml to 8ml. In the second experiment, the fertilizing frequency was changed to 2 and 3 times per growth cycle while keeping the fertilizer volume constant at its optimal level (from Experiment I). In each experiment, the plants were harvested after 10 days, and their heights were measured and recorded.

3.8 Meta-Analysis

In this meta-analysis, the aim was to estimate the average crop yields of various types of vegetable crops produced through hydroponic farming. To ensure consistent comparisons between different crop categories, the arithmetic mean of yield values (AM_y) was used as an effect size to quantify the magnitude of the variable, which remained constant for all types of crops. The AM_y effect size was calculated with the equation below:

$$AM_y = \bar{X} = \frac{\sum x_i}{n}, \tag{2}$$

where x_i is the crop yield value in kg m^{-2} $cycle^{-1}$ and n is the number of observations (Johnson and Eagly, 2014).

The AM_y calculated was not weighted for any crop categories, indicating that each observation was given equal importance and influence in the results. Since most of the studies did not report variability, the variance was not taken into account while weighting the effect size. Also, experimental studies conducted by researchers often had smaller plots with a higher level of replication; while studies on real farms, where crops usually were grown at larger spatial scales but with a lower level of replication (Payen *et al*., 2022). Therefore, for these reasons, weighting effect sizes based on the sample size was avoided in this study to ensure that it is the fairest possible comparison between each growing system (Payen *et al*., 2022).

The impact of hydroponic system, growing orientation as well as growing environment on vegetable crop yields was evaluated using one-way analysis of variance (ANOVA) method. Two-sample t-tests where unequal variances were assumed were performed at a 95% confidence level to compare the differences in vegetable crop yields between each growing system (Mathew *et al*., 2020). Data distribution and variability were visualized using boxplots. The analyses in this study were performed in SPSS 27 (IBM Corp., 2020).

3.8.1 Data Collection

In this study, reliable sources of data in the form of scientific articles, conference proceedings and academic journals from trusted research institutions, universities, and commercially viable facilities have been analyzed and reviewed in February 2023 to identify global-level peer-reviewed publications reporting vegetable hydroponic yields. To ensure a standardized reporting format, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) system was consulted and followed (Moher *et al*., 2016).

The search was performed using Scopus and IEEE Xplore database with the following search keyword string:

(“hydroponic*” OR “hydroponic horticulture*” OR “soilless agriculture*” OR “hydroponic farming*” OR “horizontal farm*” OR “horizontal agriculture*” OR “vertical farm*” OR “vertical agriculture*” OR “indoor farm*” OR “indoor agriculture* OR “controlled environment agriculture*””) AND (“vegetable*” OR “vegetable crops*”) AND (“crop yield*” OR “food productivity*”)

These search keywords are required to be present in either the title or the abstract of the publications. They narrow down the search results and make sure that the contents discussed in the papers relate to the vegetable yields of hydroponic farming. The search string’s first part specifies the results to a soilless hydroponic farming system. While the second part of search keywords is to refine the crop categories in the results to vegetables only. Only studies published in or after year 2005 were included. With the above requirements, a total of 634 papers were obtained from this initial search, 239 studies were duplicated and hence, discarded. Then, 395 studies were left for abstract and full-text screening.

These 395 publications were further refined using the following criteria:

(a) The study required to deal with at least one vegetable crop planted for food consumption.

(b) The study required to involve hydroponic farming method (pure soil-based agriculture was excluded).

(c) The study required to report the agriculture productivity or crop yields.

After the screening process, there were 68 final papers included for data extraction as shown in Figure 3.10.

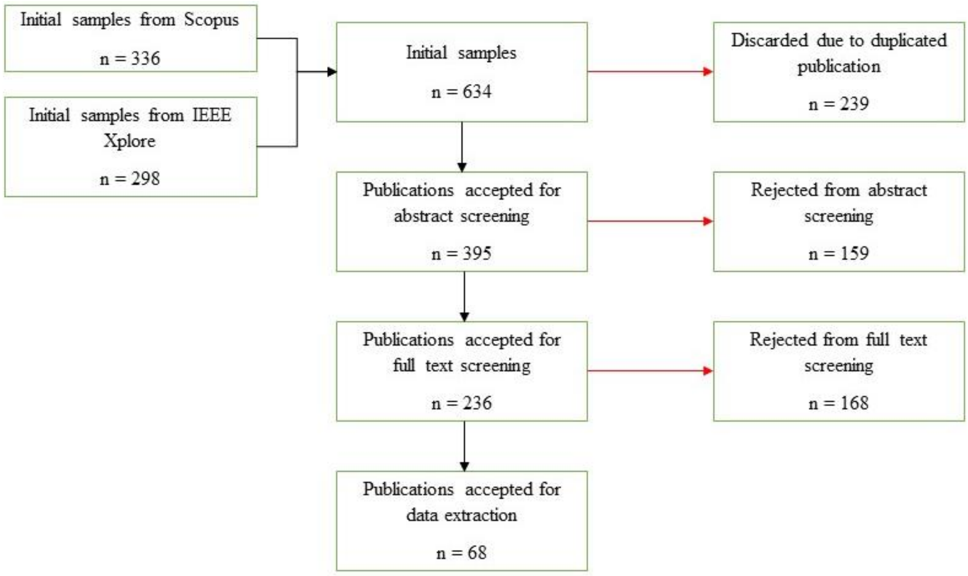

Figure 3.10 PRISMA flowchart details the steps and number of outputs for this meta-analysis.

3.8.2 Data Extraction

The crop yields per year for each study were summarized and sorted in an Excel sheet. Usually, each study involves more than one case study (observation), and each row of the Excel sheet showed each observation. For each observation, data was collected on the crop yield per year, vegetable crops grown, its growing orientation, and growing environment. This information is available in supplementary materials, S1.

However, several papers do not report the crop yields directly. In such cases, crop cut method was applied to estimate the crop yield as shown in Equation 1 (Sapkota et al., 2016).

$$\begin{aligned} &\text{Yield (weight area}^{-1}\text{ year}^{-1}) \\ &\qquad = \text{Yield per plant (weight plant}^{-1}\text{ year}^{-1}) \\ &\qquad \times\ \text{no. of plants grown in a given area (area}^{-1}) \end{aligned} \tag{1}$$

3.8.3 Categories of Crop

The information obtained from each publication was categorized based on the vegetable crop categories and their growing environment as well as orientation. Food and Agriculture Organization (FAO) has developed categories for global agricultural crops. The list of crop categories together with their global agricultural yields are available on their online website FOASTAT (FAO, 2023).

This eases the comparison between hydroponic yields with the soil-based farming yields reported by FAO in this paper. Table 3.2 shows that 13 out of 22 types of vegetable crops that are listed under the 'vegetable primary' category in the FAO crop list were involved in this study as shown in Table 3.2.

Table 3.2 List of the Vegetable Primary Categories Based on the FAOSTAT (FAO, 2023).

Crop Categories	**Crops Included in the Category**
Anise, badian, fennel, coriander (*n* = 15)	Fennel (seeds), coriander, caraway
Aubergines (*n* = 1)	Aubergines
Beans (*n* = 4)	String beans, beans
Cabbages & other brassicas (*n* = 78)	Collards, brussel sprouts, leaf mustards, cabbages, kales, kohlrabies, bok choy
Carrots & turnips (*n* = 1)	Turnips, Carrots
Chillies & peppers (*n* = 16)	Chillies, bell peppers
Cucumbers & gherkins (*n* = 19)	Cucumbers, gherkins
Lettuce & chicory (*n* = 214)	Endives, tettuces, mesclun, chicories
Onions & shallots (*n* = 5)	Onions, shallots, spring onions
Pumpkins, squash & gourds (*n* = 2)	Pumpkins, Courgettis, squashes
Spinach (*n* = 10)	Spinach
Tomatoes (*n* = 52)	Tomatoes, cherry tomatoes
Vegetables, fresh nes (*n* = 82)	Basil, beetroots, celeries,fennel (bulb), marjoram, celeriac, water spinaches, Swiss chards, parsnips, rhubarbs, radishes, water cresses

Note: Category with "nes" refer to crops not included in other categories of the same crop type and "fresh" indicates non-processed crops according to the FAOSTAT definition. The number in the brackets, n represents the number of observations for each category.

3.8.4 Yields of Conventional Soil-Based Farming

To compare crop yields between traditional soil-based agriculture and hydroponic farming systems, the FAOSTAT's global average crop yields for soil-based agriculture were utilized as a reference point. The FAO computed the global average yields of soil-based agriculture for a particular crop and year by adding up the amount of crop production in each country and dividing it by the total harvested area for the specific crop category in each country. FAO provides the most precise estimation on the average conventional farming crop yields at the global level, as it includes various growing environment such as open-air land and greenhouses. The average yields in the period of 2017 until 2021 (5 years) was computed and used for the analysis purpose.

3.9 Gantt Chart and Work Plan

Project planning of FYP1 was conducted from 13-June-2022 until 23-July-2022 as shown in Figure 3.11, which includes conducting topic research, finalizing material list, designing circuit and prototype. Then, it took almost 2 months period to execute the project in building a smart indoor hydroponic system where the plants' condition can be monitored remotely via Internet of Things.

[FYP1] Indoor hydroponics farming system monitoring via Internet of Things (IoT)

Student Name: Goh Yee Sin (1802700)

Project Start Date 6/13/2022 (Monday) Display Week 1

WBS	TASK	START	END	DAYS	% DONE	WORK DAYS
1	**Project Planning**		-			-
1.1	Title Registration	2022-06-13	2022-06-13	1	100%	1
1.2	Topic Research	2022-06-18	2022-07-08	21	100%	15
1.3	Crop Selection	2022-06-21	2022-06-24	4	100%	4
1.4	Finalise Material List	2022-06-22	2022-06-25	4	100%	3
1.5	Purchase Materials	2022-06-25	2022-06-29	5	100%	3
1.6	Circuit Design	2022-07-03	2022-07-16	14	100%	10
1.7	Prototype Design	2022-07-10	2022-07-23	14	100%	10
2	**Project Execution**		-			-
2.1	Received Purchased Materials	2022-06-29	2022-07-05	7	100%	5
2.2	Circuit Construction	2022-07-10	2022-07-30	21	100%	15
2.2.1	DHT11 Sensor	2022-07-10	2022-07-11	2	100%	1
2.2.2	DS18B20 Sensor	2022-07-13	2022-07-15	3	100%	3
2.2.3	TDS Sensor	2022-07-19	2022-07-21	3	100%	3
2.2.4	LED Grow Light	2022-07-25	2022-07-28	4	100%	4
2.3	Trial Hydroponics Farming	2022-07-13	2022-08-10	29	100%	21
2.4	IoT Platform	2022-07-30	2022-08-13	15	100%	10
2.5	ESP32-Cam System	2022-08-05	2022-08-09	5	100%	3
2.6	Prototype Building	2022-08-20	2022-09-08	20	100%	14

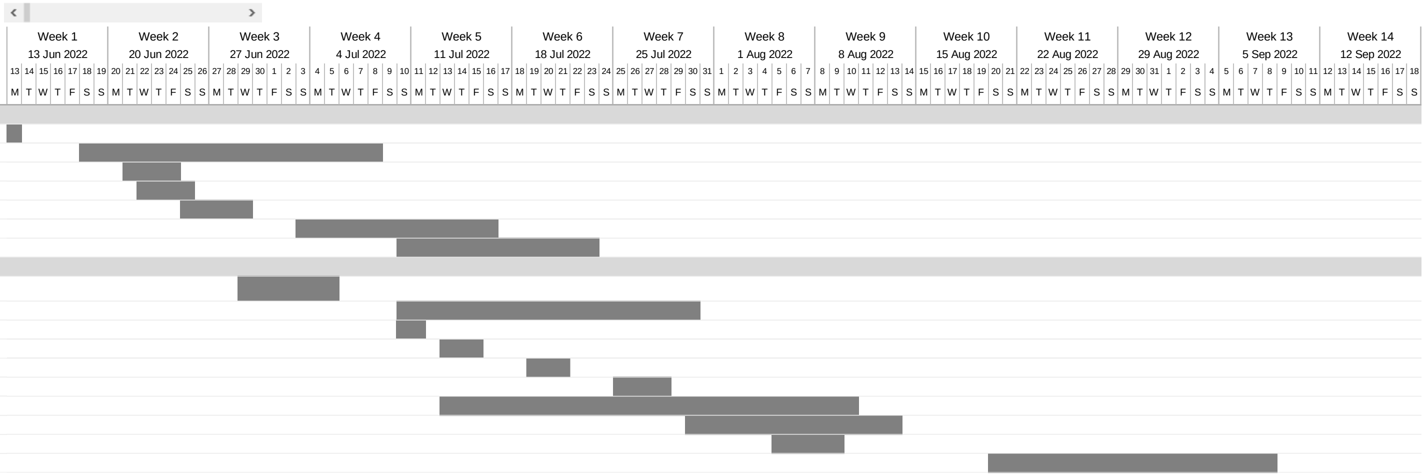

Figure 3.11 Gantt Chart for FYP1

In FYP2, the project was divided into 2 subsections (Figure 3.12). It took almost 2 months to complete the meta-analysis. Experiments to identify the optimal fertilizer volume and frequency of Bayam Hijau were conducted concurrently together with the meta-analysis.

[FYP2] Indoor hydroponics farming system monitoring via Internet of Things (IoT)

Student Name: Goh Yee Sin (1802700)

Project Start Date 1/30/2023 (Monday) Display Week 1

WBS	TASK	START	END	DAYS	% DONE	WORK DAYS
1	**Meta Analysis**		-			-
1.1	Literature Review	2023-01-30	2023-02-26	28	100%	20
1.2	Collection of Data of Global Hydroponic Yields	2023-02-15	2023-02-27	13	100%	9
1.3	Collection of Data of Soiled-Based Agriculture Yields from FAO	2023-02-26	2023-02-27	2	100%	1
1.4	Analysis of Data and Results	2023-03-03	2023-03-21	19	100%	13
1.5	Result Discussion	2023-03-18	2023-04-01	15	100%	10
2	**Experiments**		-			-
2.1	Fertilizer Volume	2023-02-20	2023-03-21	30	100%	22
2.1.1	4ml	2023-02-20	2023-03-01	10	100%	8
2.1.2	6ml	2023-03-01	2023-03-10	10	100%	8
2.1.3	8ml	2023-03-10	2023-03-19	10	100%	6
2.2	Fertilizing Frequency	2023-03-19	2023-04-07	20	100%	15
2.2.1	2 times	2023-03-19	2023-03-28	10	100%	7
2.2.2	3 times	2023-03-28	2023-04-06	10	100%	8

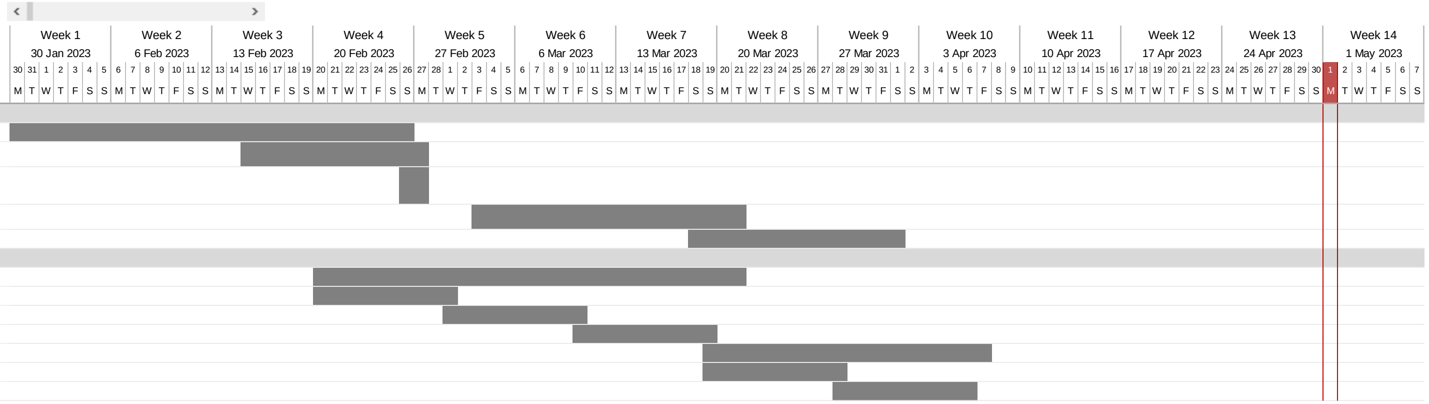

Figure 3.12 Gantt Chart for FYP2

3.10 Summary

An open loop control system was developed to continuously monitoring and recording various parameters of interest such as water temperature, EC and pH level of the nutrient solution. Experiments were designed by adjusting the fertilizer volume from 4ml, 6ml to 8ml; and the fertilizing frequency from 1, 2 to 3 times in a 10-day growing cycle. The heights of the bayam hijau crops were measured and recorded at the end of experiment to identify the optimum fertilizer volume and fertilizing frequency for bayam hijau. A global meta-analysis was performed through the process of data collection from reliable sources, data screening, and data extraction. ANOVA method was applied to evaluate the impact of hydroponic system, growing orientation as well as growing environment on vegetable crop yields.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In FYP1, a basic hydroponic farming system with IoT is developed. The setup consists of a growing tray which can grow 8 crops every time, a IoT dashboard that can display real-time growth parameters of the plants measured by various sensors including water temperature, relative humidity, environmental temperature as well as electric conductivity (EC) of the nutrient solution. Also, the on and off of the LED grow light can be controlled via the scheduler feature available on the dashboard. Moreover, a Telegram bot is created to interact with the ESP32-Cam, that allows us to request new photo from the ESP32-Cam. With that, the plants' condition can be monitored anywhere, anytime. Lastly, an experiment is conducted with a very basic hydroponic setup to determine the effect of fertilizer on the growth of water spinach.

The result from experiments conducted during FYP1 motivated me to conduct experiments on investigating the optimal fertilizer volume and fertilizing frequency of Bayam Hijau. Other than that, a global meta-analysis was conducted to review and compare the hydroponic and soil-based agriculture for a variety of crops and how does it perform in of different growing systems. The FAOSTAT's global average vegetable yields of soil-based agriculture were used as a reference to compare the crop yields between soil-based and hydroponic farming system.

4.2 Prototype

The prototype that consists of LED grow light, sensors and ESP32-Cam was created. All of these components are contained in the large transparent container as shown in Figure 4.1 and 4.2, so that it can be moved to everywhere easily.

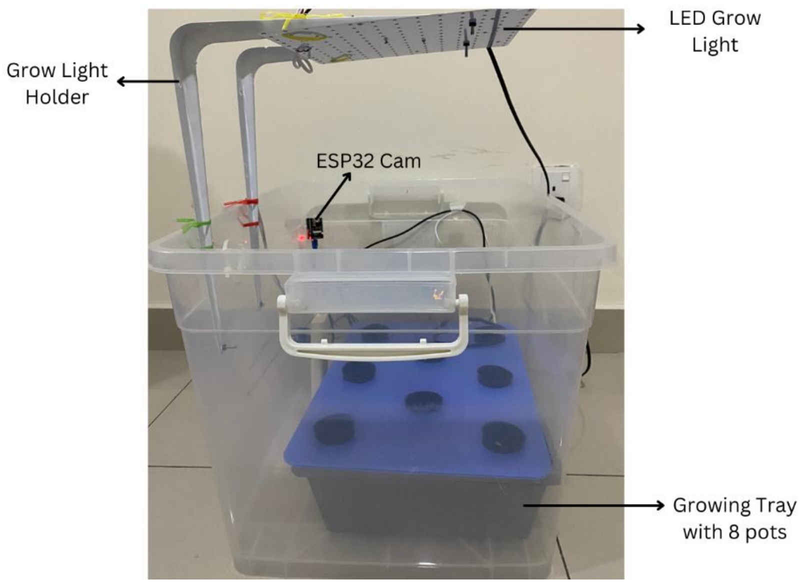

Figure 4.1 Prototype of the Project

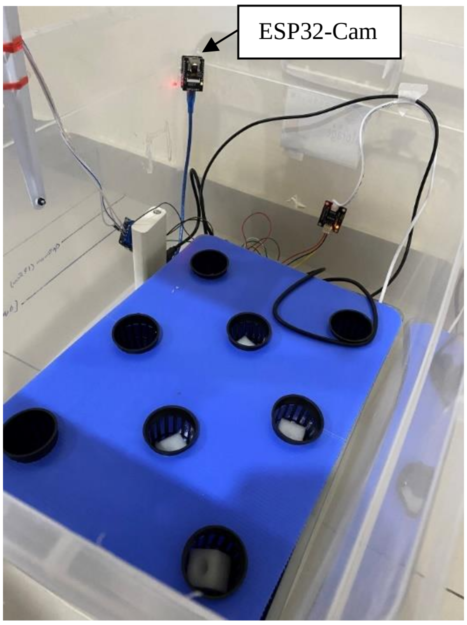

Figure 4.2 The Position of ESP32-Cam

4.3 IoT Platform - Dashboard

The dashboard was created using Cayenne, a drag and drop IoT platform. The dashboard as shown in Figure 4.3 displays the parameters measured by the sensors including the EC value, pH value and temperature of the nutrient solution, relatively humidity as well as environmental temperature. The history of the data can be tracked and visualized from the platform to ease the analysis process of the plant growth. Besides, the LED grow light can be remotely turned on and off via the scheduler function on the platform.

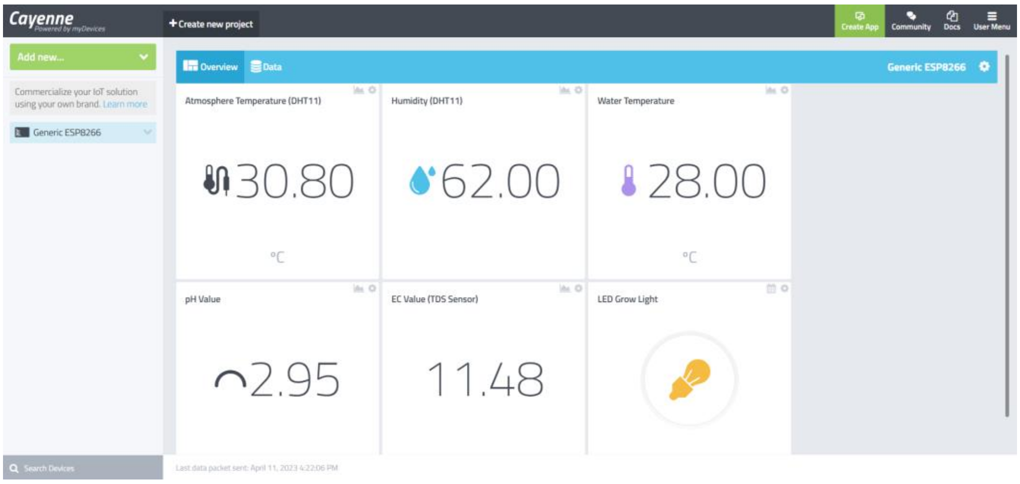

Figure 4.3 Dashboard Displayed on Website

4.4 ESP32-Cam Interact with the Telegram Bot

A Telegram bot is created where it can interact with the ESP32-Cam by typing in a particular phase. After Telegram bot receives a command from user, it will react by asking the ESP32-Cam to either take a photo, to toggle the flashlight as shown in Figure 4.4.

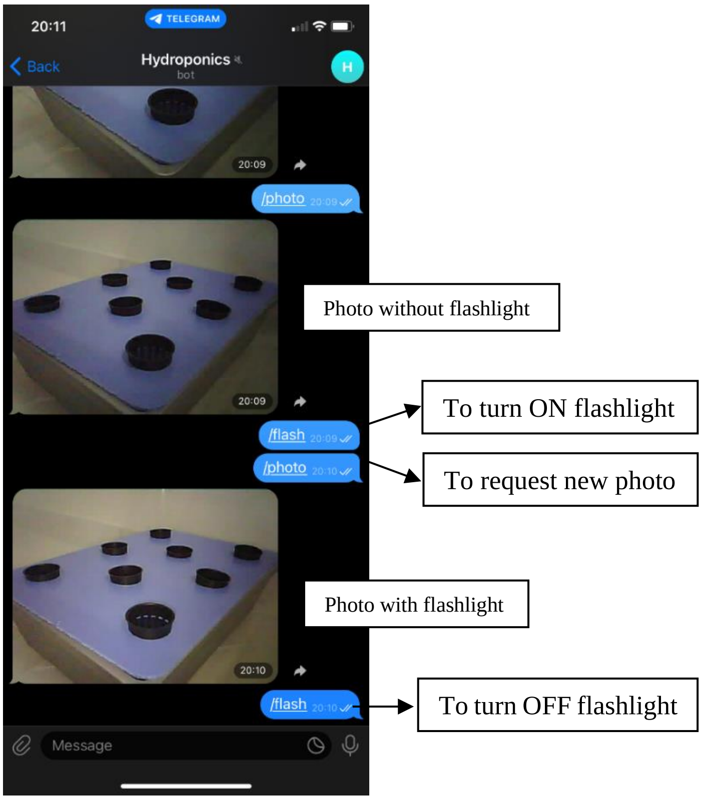

Figure 4.4 Illustration of the Interaction between ESP32-Cam and Telegram Bot

4.5 Trial Setup of Hydroponic System – Water Spinach

A very basic hydroponic setup was created using 2 plastic containers, net pots and sponge as growing medium to test growing water spinach in hydroponics. Container I contains merely water, while diluted AB fertilizer was added to Container II after one week. Fertilizer A contains potassium while fertilizer B contains sulphate and phosphate. The AB fertilizer was added to Container II biweekly as it has ideal balance of growing nutrients needed for a healthy crop. 4 water spinach seeds were added to each pot as shown in Figure 4.5 and the average germination rate is above 50%. Water is regularly added into both containers to prevent the plants from being dehydrated.

Figure 4.5 Four Water Spinach Seeds Planted in Basic Hydroponic Setup

4.5.1 Week 1

In first week, both containers contain water only without any nutrient supplied. In Container I, 2 out of 4 seeds germinated, while in Container II, 3 out of 4 seeds germinated. The maximum height of crops in Container I and II are 10cm and 9cm, respectively. At the end of first week, diluted AB fertilizer was added to Container II to compare the effectiveness of AB fertilizer in boosting the plant growth. The comparison between crops in Container I and those in Container II was shown in Figure 4.6. As shown in Figure 4.7, the root system was slowly developing to absorb water and mineral.

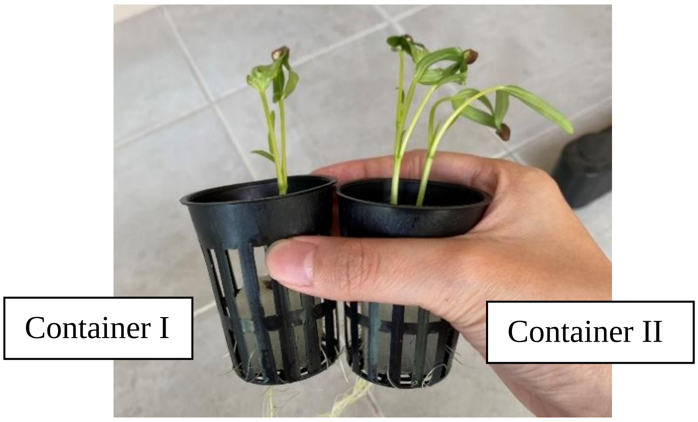

Figure 4.6 Condition of Plants after 1 Week

Figure 4.7 Root System of Crops after 1 Week

4.5.2 Week 2

The plans in Container II grows rapidly since AB fertilizer has been added into it. Figure 4.8 showed that the plants in Container II obviously grow better and healthier as compared to those in Container I. Other than comparing the height and number of leaves of the crops, the plants in Container have poorer root system. This is because the mineral in AB fertilizer helps the plants in building strong cell walls and healthy root system. Increased root growth shows that the plant can absorb more water and nutrients from the nutrient solution.

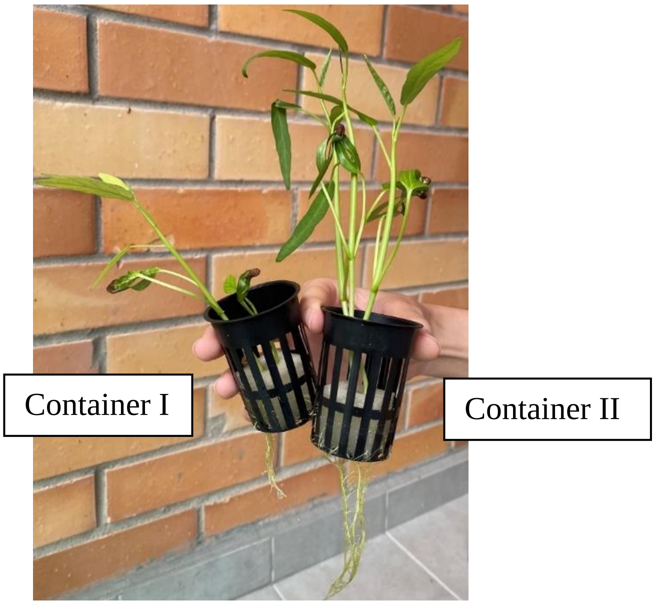

Figure 4.8 Plants Condition after 2 Weeks

4.5.3 Week 3

After 3 weeks, with sufficient nutrient provided through the hydroponic solution, the crops in Container II build thicker stem and have more leaves as compared to crops in Container I as shown in Figure 4.10. The max height of crops in Container I and II are 13.6cm and 28.7cm, respectively. This is because the essential macronutrient in the AB fertilizer encourages foliage and stem growth. Besides, as shown in Figure 4.9, the leaves of crops in Container I have begun to turn yellowish. This might be caused by nutrient deficiency since AB fertilizer was absent in Container I. The chlorophyll in leaves is used in photosynthesis. As the process of photosynthesis is disturbed due to nutrient deficiency, the chlorophyll breaks, leading to the loss of the green colour and turns yellow. Also, nutrient imbalance causes plant tissue to become papery, and the veins will become more pronounced in the leaves (Strain, 2021). Diluted AB fertilizer was added to Container II again, the EC value before and after adding fertilizer were 2.2µS/cm and 3.0µS/cm, respectively. From Figure 4.11, it can be seen that the sponge (growing medium) could not support the plant weight and hold the plants in net pot II upright. Therefore, it can be deduced that hydroponic farming method is not that suitable for water spinach due to its relatively heavy weight and thick stem.

Figure 4.9 Leaves of Plants in Container I Turn Yellow

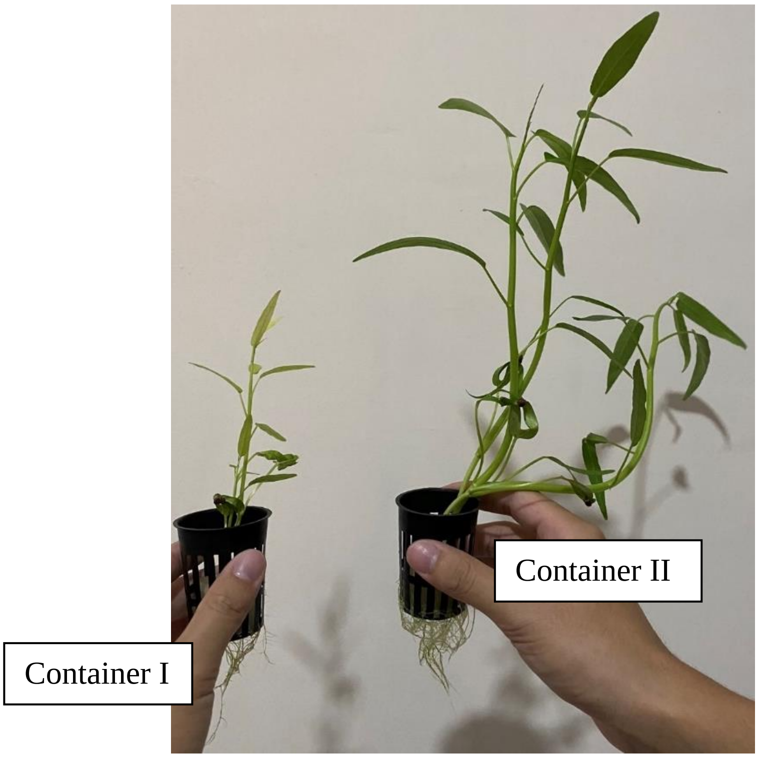

Figure 4.10 Plants Condition after 3 Weeks

4.5.4 Week 4 - Harvested

After 4 weeks, the crops in Container II grew rapidly and were ready to be harvested. Contrarily, the crops in Container I were not growing well due to nutrient deficiency. The height of crops in Container II is almost three times of the crops in Container I as shown in Figure 4.11.

Figure 4.11 Plants Condition after 2 Weeks

4.6 Experiments

4.6.1 Experiment I: Fertilizer Volume

According to the results shown in Table 4.1, an increase in fertilizer volume correlates with an increase in average plant height. Specifically, the plants grew tallest and had highest germination rate of 82.5% when 8ml of fertilizer was added to the nutrient solution.

Table 4.1 Fertilizer Volume vs. Average Plant Height

Fertilizer Volume (ml)	Average plant height in each pot (cm)									Germination Rate (%)
	1	2	3	4	5	6	7	8	Average	
4	5.30	5.30	4.77	4.83	4.73	4.70	4.83	4.83	4.91	65
6	5.28	6.28	5.30	5.23	6.20	6.05	5.23	7.38	5.87	72.5
8	6.46	7.20	6.98	6.10	6.475	6.43	6.00	6.03	6.46	82.5

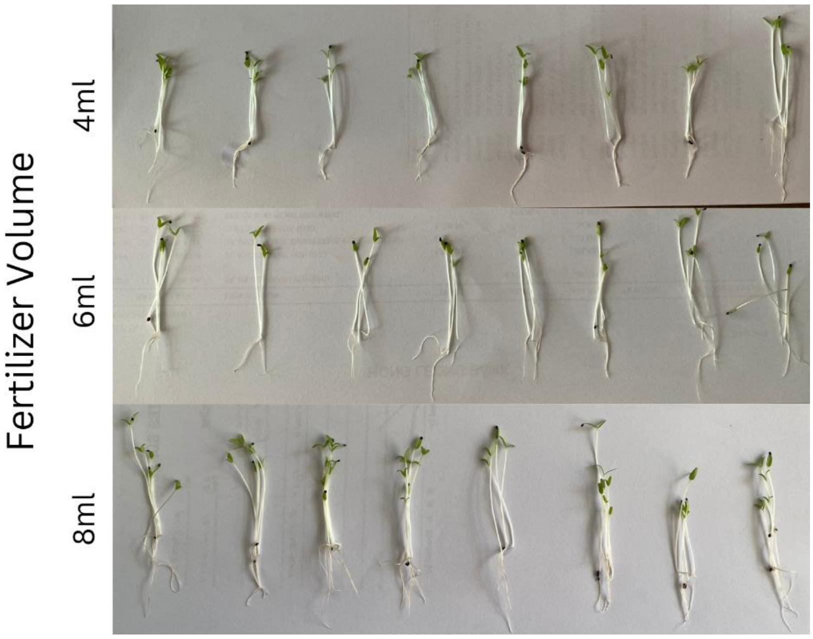

Figure 4.12 Differences in plant height when fertilizer volume increases from 4ml to 6ml to 8ml.

4.6.2 Experiment II: Fertilizing Frequency

The results in Experiment II (Table 4.2) showed that the average plant height and germination rate reached its peak when the optimal fertilizing frequency increased to twice in a growing cycle of 10 days. However, when the frequency was adjusted to thrice in a growing cycle, there was a significant decrease in average plant height as well as the germination rate. This might be due to over-fertilization, which slow or even halt plant growth over time.

Table 4.2 Fertilizing Frequency vs. Average Plant Height

Fertilizing Frequency (time(s) per 10 days)	**Average plant height in each pot (cm)**									**Germination Rate (%)**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Average**	
1	6.46	7.20	6.98	6.10	6.475	6.43	6.00	6.03	6.46	82.5
2	6.78	6.66	7.00	6.85	7.10	6.50	6.30	6.52	6.71	90

3	4.83	4.70	5.30	4.90	3.95	4.87	3.75	3.10	4.43	45

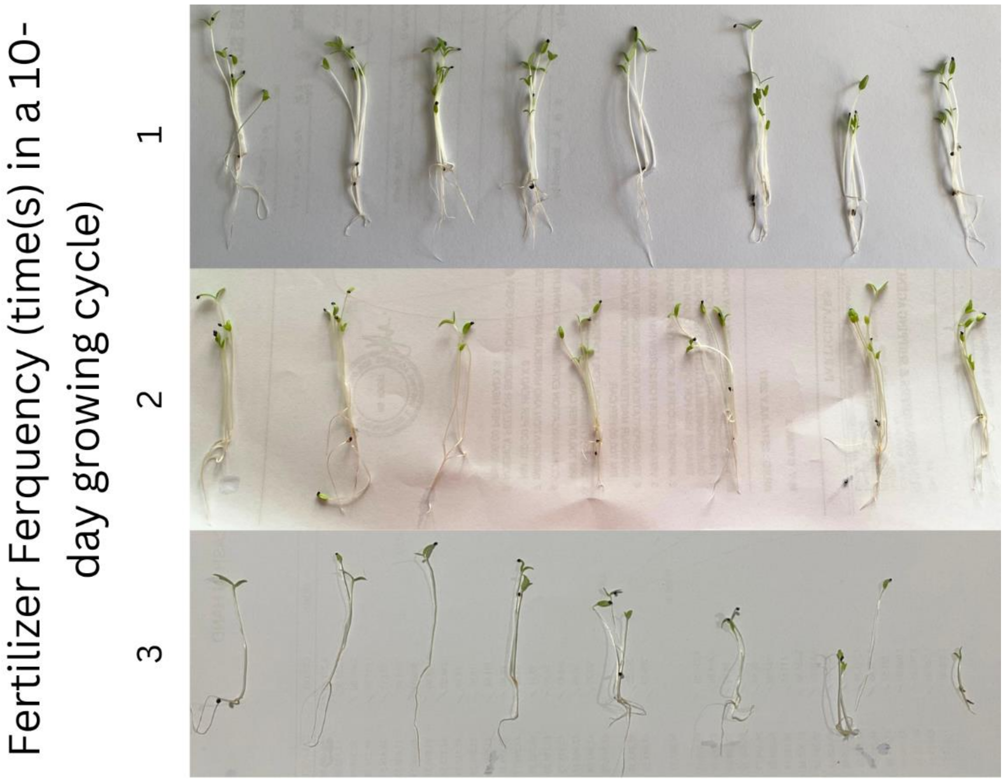

Figure 4.13 Differences in plant height when fertilizer frequency increases from 1 to 2, 3 time(s) in a 10-day growing cycle

4.7 Meta-Analysis

68 publications were included in this research study, their reported locations were shown in Figure 2. There were 499 observations of hydroponic agriculture crop yields from these 68 publications. Europe had the highest number of included studies with *n* = 203, followed by South America (*n* = 97), Asia (*n* = 91), North America (*n* = 89), Australia (*n* = 11) and Africa (*n* = 8). The top 5 countries were United States (*n* = 61), Spain (*n* = 57), Italy (*n* = 55), China (*n* = 32) and Japan (*n* = 29). 65% of the included publications reporting the hydroponic crop yields were published between 2017 and 2021 (*n* = 360). There has been an increase in the number of research regarding hydroponic agriculture, with 36 out of 68 studies published between 2019 and 2021. An overview of the data involved in this study was presented in supplementary materials, S1.

To the best of our knowledge, there are a few meta-analyses which are related to this topic, but each of them focus on different areas and scopes. Firstly, Ayipio *et al*. (2019) compared the crop yields of aquaponics and hydroponics. However, the exact crop yields for each crop were not quantified and the difference was statistically insignificant to be analyzed due to the limited number of observations (n = 50) obtained from 22 publications.

Other studies by Dorr *et al*. (2021) and Payen et al. (2022) included more observations, but they focused on food production in urban areas, where hydroponics was involved as one of the farming methods. Dorr *et al*. (2021) studied how environmental impacts like greenhouse gas emissions and water consumption level affect the crop yields in urban areas. Payen et al. (2022) covered a wider range of crops including fruits, cereals and vegetables in the comparison of crop yields between urban agriculture and conventional agriculture.

This study focused on comparing hydroponic crop fields to the conventional soil-based agriculture crop yields and identifying the most suitable farming system for hydroponics.

Figure 4.14 Global distribution of the cities where food was produced hydroponically in this meta-analysis. A city where field experiments were conducted is represented by a red dot.

The included publications involved 13 types of vegetable crops. However, those crop categories with *n* less than or equal to 5 such as “Aubergines”, “Beans”, “Carrots & turnips”, “Onions & shallots” and “Pumpkins, squash & gourds” were excluded from the analysis to avoid skewing the results. Out of the 499 observations in the sample, the category that has the most number of observations was “Lettuce & chicory” (*n* = 214), followed by “Vegetables, fresh nes” (*n* = 82), “Cabbages & other brassicas” (*n* = 78) and “Tomatoes” (*n* = 52); these were the more frequently planted vegetable crops using a hydroponic system. The other categories had lesser than 50 observations.

64.5% of the observations corresponded to horizontal farming (*n* = 322), while the remaining 35.5% of observations were for vertical farming (*n* = 177). The observations in the dataset (*n* = 236) were majority from CEA with sunlight, while 38% of observations (*n* = 191) came from CEA with artificial light. OAA was less represented in the dataset, with only 72 observations. The findings of this meta-analysis finding were summarized in Table 4.3.

Table 4.3 Summary of the meta-analysis findings. OAA refers to open-air agriculture and CEA stands for controlled environment agriculture.

No	**Crop category**	**No. of observations (*n*)**				
		Orientation		**Environment**		
		Vertical	**Horizontal**	**OAA**	**CEA with Sunlight**	**CEA with Artificial Light**
1.	Anise, badian, fennel, coriander (n=15)	14	1	5	1	9
2.	Cabbages & other brassicas (n=78)	33	45	4	15	59
3.	Chillies & peppers (n=16)	0	16	2	14	0

4.	Cucumbers & gherkins (n=19)	0	19	0	19	0
5.	Lettuce & chicory (n=24)	57	157	40	118	56
6.	Spinach (n=10)	10	0	2	0	8
7.	Tomatoes (n=52)	6	46	3	44	5
8.	Vegetables, fresh nes (n=82)	57	25	8	20	54

4.7.1 Productivity of Hydroponic Agriculture vs. Soil-Based Agriculture

The average hydroponic crop yields of each vegetable crop category included in this study are available in the supplementary materials, S1. Figure 4.15 displays a comparison between this information and the global yields of soil-based agriculture for the years 2017-2021 that were published by the FAO (2023).

Among the 8 vegetable crop categories included, 3 types of vegetables were found to be more suitable for hydroponic agriculture, these are “Anise, badian, fennel, coriander”, “Chillis and peppers” and “Cucumbers & gherkins” (Figure 4.15). The crop yields of "Anise, badian, fennel, coriander", "Chillis & peppers", and "Cucumbers & gherkins" in hydroponic systems (1.42, 15.36, and 24.53 kg m^{-2} $year^{-1}$, respectively) were 1.19 to 2.63 times higher compared to those of soil-based agriculture (0.54, 8.92, and 20.50 kg m^{-2} $year^{-1}$, respectively).

In contrast, the conventional yields of “Spinach” were significantly higher (16.35 kg m-2 year-1) compared to hydroponic yields (2.70 kg m-2 year-1), with a difference of 6 times. For the remaining crop categories, including “Cabbages & other brassicas”, “Lettuce & chicory”, “Tomatoes” and “Vegetables, fresh nes”, conventional agriculture yielded more (14.66, 11.03, 18.28 and 7.11 kg m-2 year-1, respectively) than hydroponics (10.58, 7.12, 15.94 and 5.05 kg m-2 year-1, respectively).

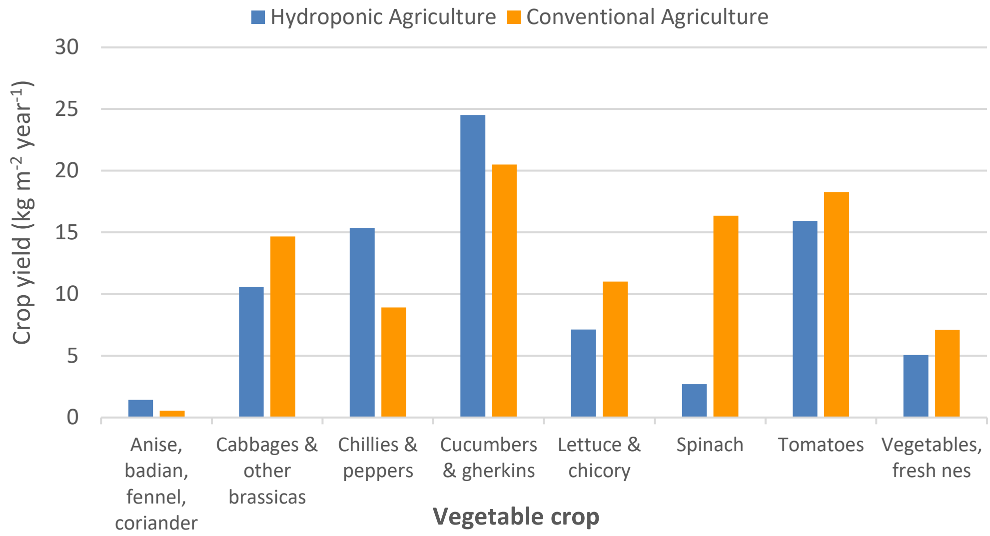

Figure 4.15 Mean crop yields per year of hydroponic agriculture (data from this study) and mean global crop yields of soil-based agriculture for 2017–2021 from FAOSTAT (FAO, 2023)

The findings of the meta-analysis indicate that hydroponic agriculture appears to be more appropriate for cultivating "Anise, badian, fennel, coriander", "Chillis & peppers" and "Cucumbers & gherkins", given that their hydroponic crop yields exceed conventional crop yields by factors of 2.6, 1.7 and 1.2, respectively (Figure 4.15). However, it is important to note that not all types of vegetables are suitable for hydroponic cultivation. Gashgari *et al*. (2018) reported that the efficiency of hydroponic system is limited by the type of crops, such as those that require a larger growing space (e.g. cabbage), have extensive root systems (e.g. onion), bear larger size fruits (e.g. watermelon) or grows on vines (e.g. squash).

Focusing on the "lettuce", Barbosa *et al*. (2015) reported that the hydroponic system (41 ± 6.1 kg m^{-2} $year^{-1}$) delivered 11 ± 1.7 times greater than that of its soil-based traditional agriculture crop yields (3.9 ± 0.21 kg m^{-2} $year^{-1}$) with up to 92% lower water usage. Gashgari *et al.* (2018) mentioned that hydroponic can achieve around 20 – 25% higher crop yields than geoponics with productivity of 2 – 5 times higher. Several studies also concluded that hydroponic system is able to produce higher quality crops with higher yields (Sardare, 2013; Lee and Lee, 2015; Majid *et al.*, 2021). In contrast, this meta-analysis showed that conventional agriculture (11.03 kg m^{-2} $year^{-1}$) had higher crop yield than the hydroponic system (7.12 kg m^{-2} $year^{-1}$). This difference could be explained by the large difference in the number of observations in estimating the yields. This study had a significantly higher number of observations (*n* = 214) in comparison to Barbosa et al.'s (2015) study (*n* = 3). Besides, the differences might also be due to latitudinal variation of crop grown as shown in Figure 4.13. For example, the crop yield of same species of "Lettuce", Romaine Lettuce, grown under horizontal agriculture in Uvalde with latitude of 29.2097° N, 99.7862° W (20.50 kg m^{-2} $year^{-1}$) had almost 3 times higher yields than in Lancaster with latitude of 54.0449° N, 2.7993° W (6.90 kg m^{-2} $year^{-1}$),

The result showed that the performance of "Spinach" is 6 times better in soil-based farming system than in hydroponic system. This might due to the spinach is a heavy feeder that requires a lot of nutrients to grow healthily. Soil acts as a natural reservoir of nutrients that gradually releases them to the cops to maintain optimal nutrient balance. Furthermore, spinach is often susceptible to root diseases. It would be easier to be controlled in soil due to the presence of soil microbes. Beneficial soil microbes like Pseudomonas spp are able to provide strong protection and resistance to the root infectious diseases through its antagonistic property (Mehta et al., 2014). Hence, root diseases can spread more quickly and hard to control in a soilless farming method. However, these results conflicted with Syed *et al.* (2021) who suggested that hydroponic technology could increase crop yields of spinach by up to 25%. Hassall & Associates Pty Ltd (2001) mentioned that not all crops are suitable for growing hydroponically, hence the hydroponic technology is unconvincingly to displace soil production for bulk commodity items.

4.7.2 Horizontal vs. Vertical Farming

Figure 4.16 shows crop yields per year between vertical and horizontal farming method of hydroponic system. The crop categories that had less than 6 observations in either vertical or horizontal farming method were excluded from the comparison. The farming orientation significantly affected the crop yield for "Lettuce & chicory" (p=0.0000) and "Vegetables, fresh nes" (p=0.0155), but not for "Cabbages & other brassicas" (p=0.7272) nor for "Tomatoes" (p=0.3091). For "Lettuce & chicory", vertical farming (17.81 kg m^{-2} $year^{-1}$) had

4.5 times better performance than horizontal farming (3.95 kg m^{-2} year^{-1}), whereas horizontal farming (10.91 kg m^{-2} year^{-1}) led to 4.6 times higher crop yields than vertical system (2.37 kg m^{-2} year^{-1}) for "Vegetable, fresh nes". The variability of the crop yield values in each category was considered very high. For instances, in the category of vertical farming of "Lettuce & chicory", the minimum yield value was 1.00 kg kg m^{-2} year^{-1} and the maximum value was 103.60 kg m^{-2} year^{-1}.

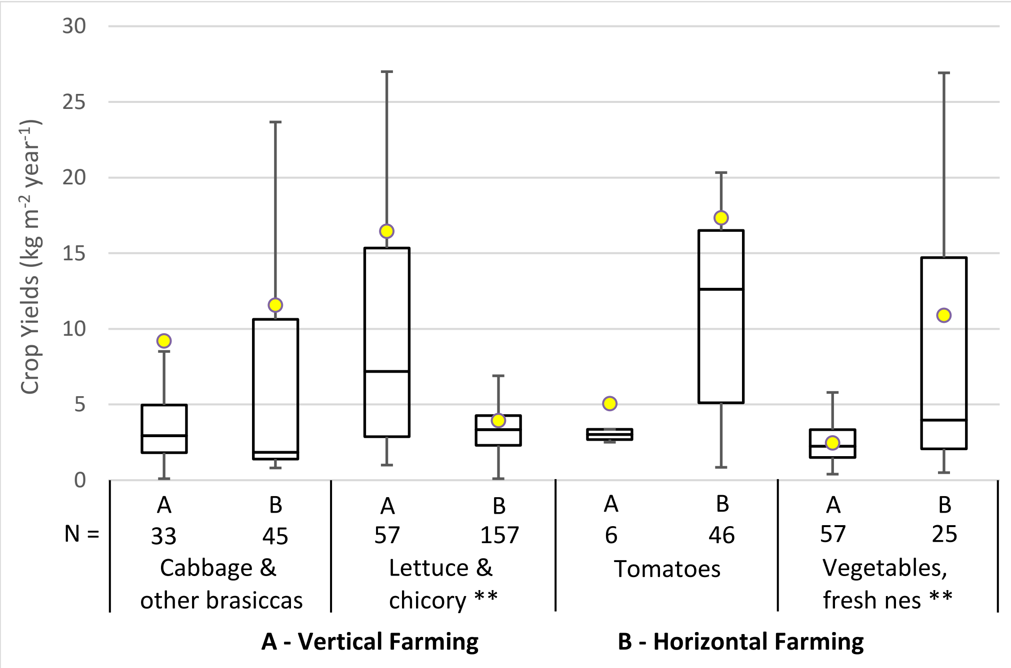

Figure 4.16 Differences in crop yields per year between vertical and horizontal farming method of hydroponic system for 4 categories of crops, the other 4 categories were excluded due to limited observations (n < 6). The measurement of crop yields in vertical farming involved the determination of the total weight of crops from all the stacked growing layers per square meter of ground area. The bottom end of the box represents the first quartile, the line that split the box into 2 is the median, and the top end of the box represents the third quartile. The 2 error bars outside of the box depict the minimum and maximum yield values within the distance of 1.5 times of the interquartile range of the lower and upper quartiles. Yellow dots define the mean. ** = $p < 0.05$ (one-way analysis of variance test).

It was unsurprising that the variations in crop productivity across different growing systems were not only influenced by the growing conditions and orientations but also depended on the specific crop types. Only two categories were found to have significant difference in farming orientation, “Lettuce & chicory” and “Vegetables, fresh nes” (Figure 4.16). Vertical farming performed better than horizontal farming for “Lettuce & chicory” whereas the reverse was observed for “Vegetables, fresh nes”. This can potentially be explained by a wide variety of vegetables were categorized into a disaggregated crop category.

For example, in the category of “Lettuce & chicory”, the types of lettuce grown in vertical and horizontal farming can differ greatly, with vertical farming welcoming mostly lettuces with large heads (e.g., Butterhead lettuce) and horizontal farming mainly growing leafy lettuces with smaller head sections (e.g., Waldman's Green), leading to very high variability in vertical farming of “Lettuce & chicory”; the minimum yield value was 1.00 kg m^{-2} $year^{-1}$ and the maximum value was 103.60 kg m^{-2} $year^{-1}$. Similar observations were made in the “Vegetable, fresh nes” category, that comprised diverse types of crops, where it was not necessary to have the same type of crop in the vertical and horizontal farming in the included studies.

Due to insufficient data in some categories for analysis purposes and high variability in the data, an overall trend regarding the best growing orientation could not be observed, this remains to elucidated when more evidence becomes available in the future.

4.7.3 OAA vs. CEA

Figure 4.17 shows the crop yields per year of OAA and CEA for various vegetable categories. The farming system's growing environment had a significant impact on yields for “Anise, badian, fennel, coriander”, “Cabbages and other brassicas”, “Lettuce & chicory”, and “Vegetable, fresh nes” ($p=0.0000$ for all), but not for “Chillis & peppers”, “Spinach”, and “Tomatoes”. CEA with artificial light had significant effect on the crop yields of “Anise, badian, fennel, coriander” (2.11 kg m^{-2} $year^{-1}$), which is 7.5 times higher than OAA (0.28 kg m^{-2} $year^{-1}$). The use of CEA with sunlight significantly affected the crop yields of "Cabbages & other brassicas" (31.62 kg m^{-2} $year^{-1}$), which were 27 times higher than those of OAA (1.17 kg m^{-2} $year^{-1}$) and 5.4 times higher than those of CEA with artificial light (5.89 kg m^{-2} $year^{-1}$). Similarly, for

"Vegetable and fresh nes", the average yields of CEA with sunlight (13.62 kg m^{-2} $year^{-1}$) were higher than those of CEA with artificial light (2.24 kg m^{-2} $year^{-1}$) and OAA (3.49 kg m^{-2} $year^{-1}$). For "Lettuce and chicory", the crop yields of CEA with artificial light (16.75 kg m^{-2} $year^{-1}$) were much higher than those of OAA (2.55 kg m^{-2} $year^{-1}$) and CEA with sunlight (4.39 kg m^{-2} $year^{-1}$). The dataset also showed high variability in OAA and CEA, such as "Cabbages and other brassicas" having a minimum crop yield of 1.70 kg m^{-2} $year^{-1}$ and a maximum crop yield of 140.31 kg m^{-2} $year^{-1}$ in the "CEA with sunlight" category.

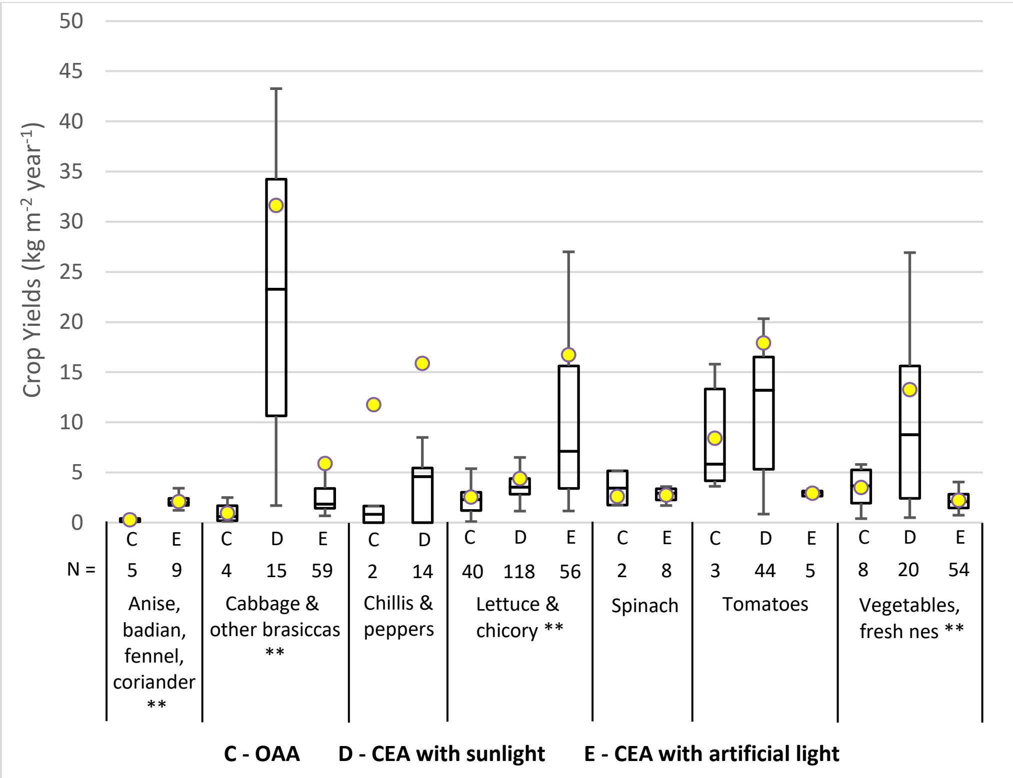

Figure 4.17 Differences in crop yields per year between open-air agriculture (OAA) and controlled-environment agriculture (CEA) for 7 categories of vegetable crops. The bottom end of the box represents the first quartile, the line that split the box into 2 is the median, and the top end of the box represents the third quartile. The 2 error bars outside of the box depict the minimum and maximum yield values within the distance of 1.5 times of the interquartile range of the lower and upper quartiles. Yellow dots define the mean. ** = $p < 0.05$ (one-way analysis of variance test).

Note: For "Anise, badian, fennel & coriander" and "Spinach", there was no observation for growing system D (CEA with sunlight); while for "Chillis & peppers", the observation for *growing system E (CEA with artificial light) was absent; and for "Cucumbers & gherkins", there was no observation for both D and E thus not plotted.*

As for the controlled environment with either sunlight or artificial light versus open-air agriculture (CEA vs. OAA), the former led to significantly higher crop productivity compared to the latter for all the significant different vegetable crop categories (Figure 4.17). If included the insignificant different categories, only "Spinach" had higher crop yields in the OAA compared to CEA, this might be due to low number of observations (n = 2 in OAA vs. n = 8 CEA) and some explanations raised in section 4.2 could potentially be applied too.

The combination of CEA with hydroponic technique offers an optimal growth environment by monitoring and controlling the growth factors such as lighting, water, nutrient levels and ventilation, while minimizing the exposure to pests and diseases. With the protection provided by the sheltered CEA, it enables the vegetable crops to produce high quality food year-round with minimal inputs, regardless of seasons and climate (Benke and Tomkins, 2017). For example, the average yield of "Cabbages and other brassicas" was the highest for CEA with sunlight system (31.62 kg m^{-2} $year^{-1}$), almost 2.2 times higher than the conventional yields (14.66 kg m^{-2} $year^{-1}$) as shown in Figure 4.17. The overall results showed that growing crops in controlled environment is more productive with higher yields.

4.8 Summary

A hydroponic monitoring system was developed with various sensors to detect the growth parameters and an IoT platform to display the parameters. Monitoring of crop condition can be achieved by the interaction between ESP32-Cam and a created Telegram bot. The results from the experiments conducted showed that the optimal fertilizer volume and frequency were 8ml at twice in a 10-day growing cycle, respectively. From meta-analysis, hydroponic agriculture led to higher yields than conventional agriculture for "Anise, badian, fennel & coriander", "Chillies & peppers" and "Cucumbers & gherkins". The vegetable crops were grown in diverse conditions, the growing orientation (vertical or horizontal) significantly influenced "Lettuce & chicory" and "Vegetables, fresh nes", but an overall trend regarding the best growing orientation could not be observed. In terms of growing environment such as controlled and open-air setups, crop yields of CEA were significantly higher than those of OAA for “Anise, badian, fennel & coriander”, “Cabbage & other brassicas”, “Lettuce & chicory” and “Vegetables, fresh nes”.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The aim of this project is to develop a smart indoor hydroponic farming system with IoT technology to monitor the crops' condition as well as to enhance public understanding of hydroponics' potential for food production. A hydroponic monitoring system equipped with various sensors and camera system was developed to continuously monitor the growing parameter of the crops. Based on the results of the conducted experiments, 8ml of fertilizer with the frequency of twice in a 10-day growing cycle is optimum for Bayam Hijau.

The meta-analysis showed that "Lettuce & chicory" was studied the most. Hydroponic agriculture led to higher yields than conventional agriculture for "Anise, badian, fennel & coriander", "Chillies & peppers" and "Cucumbers & gherkins". The vegetable crops were grown in diverse conditions, the growing orientation (vertical or horizontal) significantly influenced "Vegetables, fresh nes" and "Lettuce & chicory", but an overall trend regarding the best growing orientation could not be observed. In terms of growing environment such as controlled and open-air setups, crop yields of CEA were significantly higher than those of OAA for "Anise, badian, fennel & coriander", "Vegetables, fresh nes", "Lettuce & chicory" and "Cabbage & other brassicas". In short, this study seeks to provide more solid evidence of the crop yields for hydroponic agriculture and determines the better hydroponic growing environment. This can contribute to improving the crop productivity and the global food self-sufficiency, as well as self-sustainability.

5.2 Recommendations for Future Work

A smart hydroponic monitoring system can be enhanced with machine vision to detect the yellowish or dotted patterns on the leaves of crops. This can help in identifying and diagnosing plant diseases at an early stage, which is crucial in preventing the spread of the disease to other plants in the same system since their root systems are submerged in the same nutrient solution. Machine vision technology can analyze images of the plants captured by cameras installed within the hydroponic system. The images can then be analyzed using algorithms designed to detect specific patterns and color changes associated with plant diseases. The system can then alert the user to the presence of the disease, and helps to reduces the need for manual inspection of plants, which can be time-consuming and labor-intensive.

The comparison of hydroponic crop yields between various growing systems in this current literature was not fair due to the varies in exact type of crops grown, composition of the nutrient solution, latitude of the agricultural land (for crops grown in open air environment) and other factors, the crop yields might be affected accordingly. Future studies should focus on performing literature search by a more efficient method. For example, conducting sensitivity study to the hydroponic yield value in order to determine the most important growing factor as in growing orientation and environment which lead to the highest increase in the crop yields. The results could then help the farmers to focus on these parameters to boost the crop productivity.

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