Study of the Effect of Physical Parameters on Commercial Hydroponics Based on Internet of Things (IoT): A Case Study of Bok Coy Plants (*Brassica rapa*) and Water Spinach (*Ipomoea Aquatica*)

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Abstract: Population growth causes the demand for food to increase. One solution that can be applied is agriculture with hydroponic technology. To increase production efficiency, one must know the physical parameters that most influence the production process. This research used an IoT system to gather accurate and precise measurement data of physical parameters to be used as a dataset for machine learning. The dataset consisted of light intensity, humidity, air temperature, and total dissolved solids (TDS). Plant growth was measured by leaf area of the plant, number of leaves, and plant stem length every 3 to 4 days. The models used in the machine learning process were linear regression, polynomial regression, and random forest regression. The machine learning results showed that the best model for predicting plant growth was random forest regression with an MAE of 8.3% and an R^2 of 0.93, for both bok coy and water spinach. The variables that influence growth the most are TDS and light intensity. According to the relationship between TDS gradient and plant growth gradient, the most optimal growth can be achieved by raising the TDS gradient or by maintaining a high TDS, which can be achieved by adding nutrient solution to the tank regularly.

Keywords: *bok coy; hydroponics; IoT; machine learning; water spinach.*

1 Introduction

Indonesia's population growth has resulted in an increase in domestic demand for food such as vegetables. This increase in food demand often cannot be met with conventional farming methods. Data from Badan Pusat Statistik (BPS) of Bandung city show that from the year 2021 there was a reduction of farming area [1]. Thus, we need farming methods that need only minimum farming area but are still able to produce a maximum number of vegetables. One such method is hydroponics farming.

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Hydroponics is a method of farming by utilizing water to supply plants with their nutritional needs. Two vegetables that can be grown using hydroponics are bok coy and water spinach. These vegetables are also quite popular within the Indonesian community [1]. Benton [3] explained that advantages of hydroponics compared to conventional farming are a more thorough control across the entire farming system and higher efficiency of nutritional absorption. According to Zhang *et al.* [4] less water is required for hydroponic cultivation than the water required for conventional cultivation on soil, while hydroponics can also produce more food.

As plants grow, their size, weight, volume, and form change. There are many requirements to make plant growth optimal, such as, nutrients, light, water, temperature, and air. If there is a deficit in one of them, the growth will be interrupted, or worse, the plant may die. To increase production efficiency, the farmer will need to know the effect of various existing physical parameters, such as temperature, humidity, light intensity, nutrient, and so on, on plant growth. This complex interaction can be modeled using an IoT system and machine learning, as already done previously by many researchers, such as Srinidhi *et al.* [5], Crisnapati *et al.* [6], Gerthphol *et al.* [7], Sambo *et al.* [8], Mohmed *et al.* [9], and Sarala [10]. These papers discussed the application of IoT in hydroponic systems. In our research, we added a light intensity sensor and analyzed the parameters that influence crop production and how large their effect is. This is important, because to increase crop production we must know the parameters that determine plant growth. In this study, we found that TDS is the most important feature to achieve optimum bok coy and water spinach growth.

The main purpose of the IoT system in this paper was to act as a data miner that accurately and precisely measures physical parameters such as light intensity, humidity, nutrient, and temperature. The data were stored so that they could be analyzed further using machine learning, as explained by Bahga and Madisetti [11]. From the data obtained, we determined the growth rate of the plants and the optimum value of each parameter for plant growth. This is needed in order to help farmers optimize plant growth and increase their crop production.

This study used an IoT system consisting of several sensors, i.e. DHT22 (temperature and humidity), GL5528 (light intensity sensor), DS18B20 (nutrient solution temperature), and DFR0300 (total dissolved solids), with ESP8266 as microcontroller, and Message Queueing Telemetry Transport (MQTT) as communication method. For the machine learning process this study used linear regression, polynomial regression, and random forest regression.

2 Methodology

In general, the design aims to increase the efficiency of existing bok coy and water spinach vegetable production, starting from designing and building an IoT instrumentation system to monitor the physical parameters around the plants, building a database from the data gathered, and then modeling plant growth with the obtained data using machine learning to characterize the physical parameters and determine the parameters that affect growth the most.

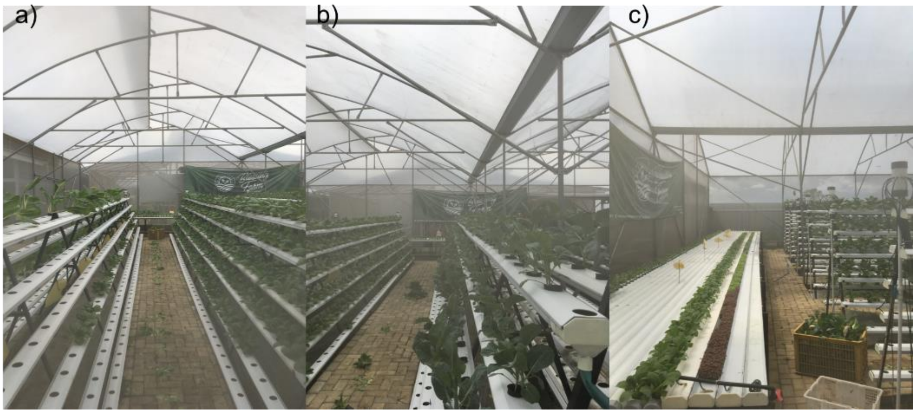

Figure 1 Inside Blessing Farm greenhouse: (a) first and second frame, (b) third and fourth frame, and (c) side view of the frames.

The research location was a commercial hydroponic greenhouse called Blessing Farm in Parongpong sub-district, Bandung city, West Java province, Indonesia. The greenhouse had an area of 14 x 15 m^2, it consisted of six frames, and used filters on the roof and walls, as can be seen in Figure 1. The left and middle picture show different frames. These pictures were taken on June 20, 2021.

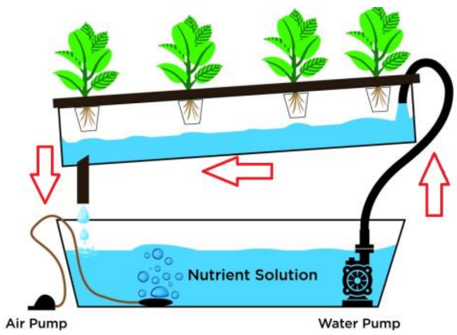

Figure 2 Diagram of nutrient flow technique (NFT).

There are many techniques in hydroponic systems. The nutrient flow technique (NFT) is the most popular system [12] and is used by Blessing Farm. NFT uses a shallow flow of water to supply plants with enough nutrients, water, and oxygen without fully submerging the plant roots. An NFT system works simply by using a water pump to circulate the water [12]. Figure 2 depicts a simple NFT system. Blessing Farm cultivates many different plants, such as lettuce, spinach, kale, water spinach, and bok coy. This study focused on bok coy (Brassica rapa) and water spinach (Ipomoea aquatica). Bok coy has green leaf blades with white bulbous bottoms [13], while water spinach is arrowhead-shaped [14,15].

As plants grow, their size, weight, volume, and form change. Major physical parameters determining their growth are light, humidity, temperature, nutrients, and weather. This research focused on light, temperature, humidity, and nutrients. We will discuss the effects of these physical growth parameters on crop production in view of optimizing the amount of photosynthesis per unit of area per unit of time, as explained by Jeannie and Berlin [16].

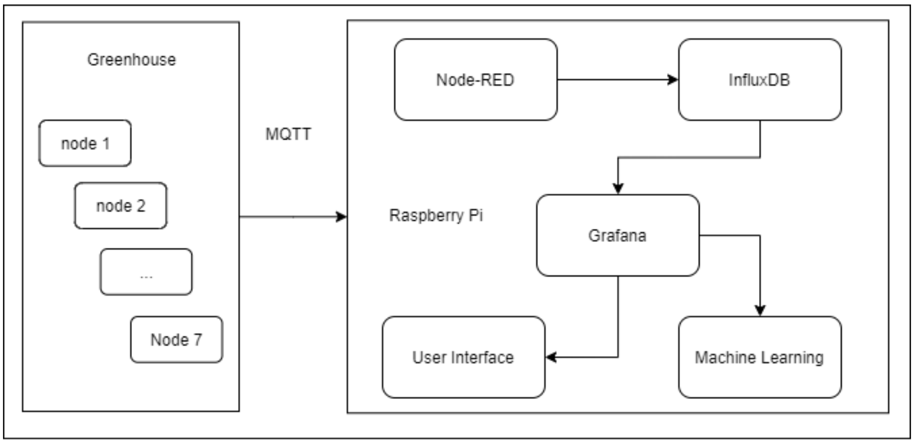

Figure 3 Flowchart for the system.

Light, what we refer to as photons, causes a change in molecules during the photochemical reaction according to the Stark-Einstein Law, but the process of photosynthesis takes a large number of photons (8-20). Light not only affects photosynthesis in plants. Light is involved in the orientation of plants, sleep movements, leaf morphology, physiology, etc. [16]. In this research, we measured light intensity using a GL5528 photoresistor.

Plants have similar mineral requirements. There are sixteen mineral elements on earth required by all plants [16]. Plants need carbon, oxygen, hydrogen, nitrogen, potassium, calcium, magnesium, phosphorus, and sulfur in large quantities, while they need chlorine, iron, boron, manganese, zinc, copper, and molybdenum in smaller quantities [16]. In this research, the nutrients needed were measured using DS18B20 for nutrient solution temperature, and DFR0300 for total dissolved solids.

Other parameters that affect plant growth are temperature and humidity. When the temperature is high but humidity is normal, the number of stomates that open will increase, letting in CO_2 for photosynthesis. If humidity is low and the plant is wilting, the number of stomates that close will increase, thereby reducing photosynthesis activity and ultimately plant growth. In this research, temperature and humidity were measured using DHT22. DHT22 is better than DHT11 in several aspects, such as temperature range, temperature accuracy, humidity range, and humidity accuracy [17].

The instrumentation system consisted of seven nodes of sensors, Message Queueing Telemetry Transport (MQTT) for communication, and a Raspberry Pi as server. The nodes used DHT22 for air temperature and humidity, photoresistor GL5528 for light intensity sensor, DS18B20 for nutrient solution temperature, and DFR0300 for total dissolved solids, with ESP8266 and ESP32 as microcontrollers. MQTT is a protocol to publish/subscribe; it is lightweight messaging and very simple. It can be used in unreliable networks or low-bandwidth conditions. It can also provide easy communication between the Raspberry Pi and many nodes, as stated by Chooruang and Meekul [18] and Anca *et al.* [19]. Figure 3 shows the general workflow of the system. All the nodes will send data to the server. The data are then processed before being saved in InfluxDB. The user can then view the data as a graph with Grafana or use it for further analysis using machine learning.

Figure 4 shows the placement of the nodes and the general structure of the greenhouse. Nodes 1 through 6 were placed inside the greenhouse at three different heights, while node 7 was placed outside. As a reference, this node placement was intended to capture the condition of the whole greenhouse. All six sensor nodes covered the measurement area based on the sensor range data in the datasheet details.

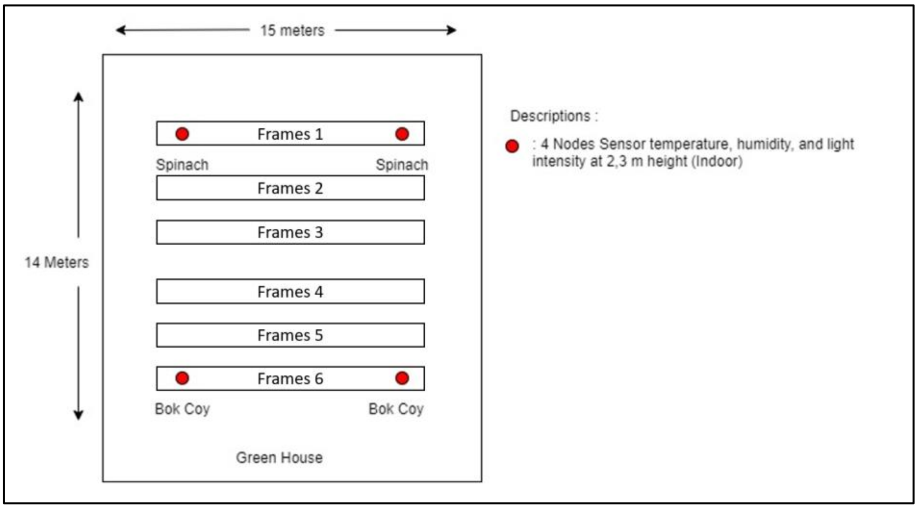

Figure 4 Greenhouse and node placement.

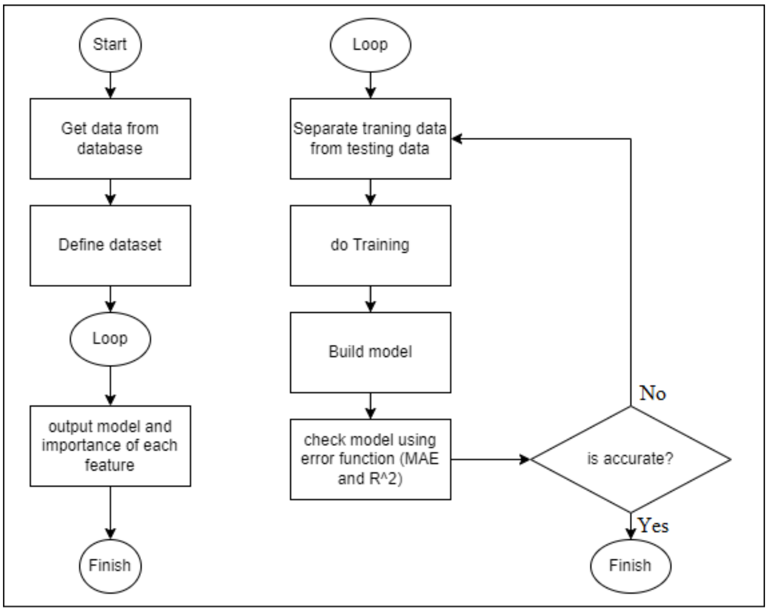

Figure 5 Flowchart of machine learning program.

For the machine learning process, this study used linear regression, polynomial regression, and random forest regression. These three models were compared by their coefficient of determination (R^2) and mean absolute error (MAE), as explained by Chicco *et al.* [20]. Temperature, humidity, light intensity, and TDS were used as the independent or x variable with plant growth as the dependent or y variable of each model. Plant growth was measured by leaf area of the plant, number of leaves, and plant stem length every 3 to 4 days. Measurements were carried out for 56 days, or two harvests. Figure 5 shows the flowchart of the machine learning program used in this paper. We used SCIKIT Learn, which was developed using Python version 3.9, for creating the models.

3 Results and Discussions

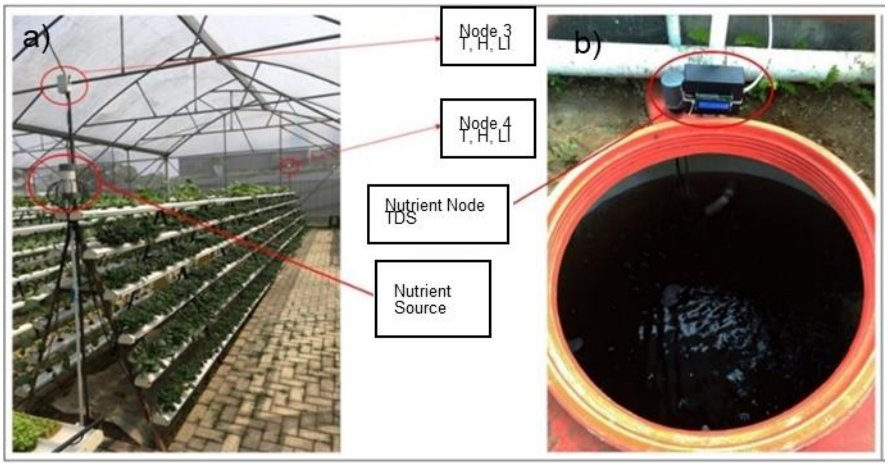

Figure 6 (a) The placement of sensor node 3, node 4, and the nutrient source. (b) The placement of the nutrient node.

An example of some of the installed nodes can be seen in Figure 6. Each node sends a JSON formatted data every three minutes. Each node is also equipped with an LED that will flash red when it has successfully sent the data. After sending the data, each node enters into a deep sleep state to save electricity.

An example of a sensor node is shown in Figure 7. It consists of waterproof box made from acrylonitrile-butadiene-styrene (ABS) material. There are hoops in the back that are used for erect pole installation. The different parts of the sensors were all connected and placed inside and outside the box and then connected with the electricity net. We used a Power Supply Stepdown AC-DC 5V 700 mA. The measurements in the greenhouse were successfully carried out by the IoT system, as can be seen in the following figure.

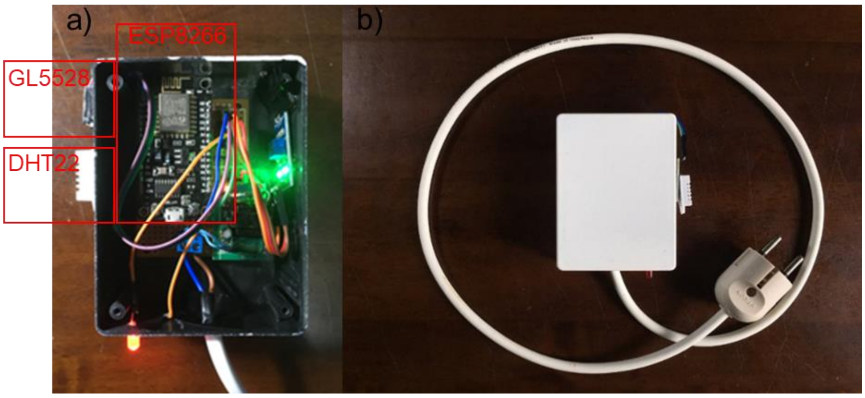

Figure 7 The structure of the sensor nodes: (a) interior view, (b) external appearance.

Figure 8 Air temperature, humidity, and light intensity time-series graph sample.

The graphic display on the Raspberry Pi connected to a monitor and running Grafana is shown in Figures 8 and 9. Looking at the air temperature and humidity graph in Figure 8, we can see that they are opposing each other, indicating that the reading is in accordance with natural conditions, where humidity is low when temperature is high and vice versa. We can also see that the light intensity reading shows a peak during the day and a valley at night.

Finally, the TDS graph can be seen in Figure 9. The TDS chart does not have a definite pattern because it is relative to the addition of fertilizer to the nutrient solution by workers.

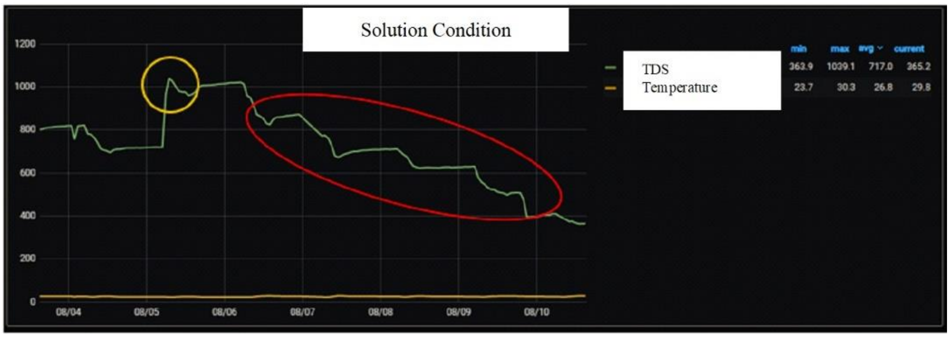

Figure 9 Total dissolved solids time-series graph.

The yellow circle shows when a worker was adding fertilizer, causing the reading to jump up and then it starts decreasing over time, indicating that the plants are absorbing nutrients, as can be seen in the area with red circle.

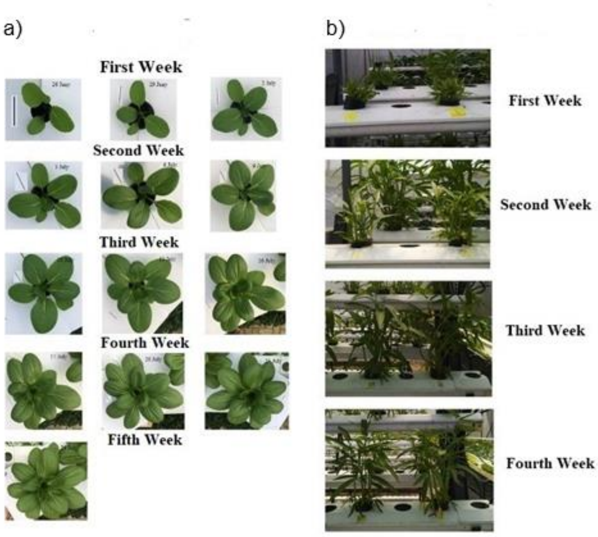

Figure 10 Results of weekly measurements for: (a) bok coy and (b) water spinach.

Plant growth can be seen in Figure 10. To quantify plant growth, we measured the leaf area of the plant, number of leaves, and plant stem length every 3 to 4 days for 4 to 5 weeks. The leaf area and stem length measurements were done by photographing the plants and then comparing pixels to a reference line for a known length, while the number of leaves was measured by manually counting the leaves on each plant. Measurements for both bok coy and water spinach started at the same time, but due to unfortunate circumstances, the bok coy measurements had to be restarted several weeks into the research.

Because the bok coy stem length and number of leaves stopped increasing after a certain time while the leaf area still continued to grow, we decided that bok coy growth is best illustrated using leaf area, while for water spinach new leaves will sprout continuously. The water spinach stem also grows longer continuously, hence, for the water spinach we decided that the number of leaves and the stem length were the best parameters.

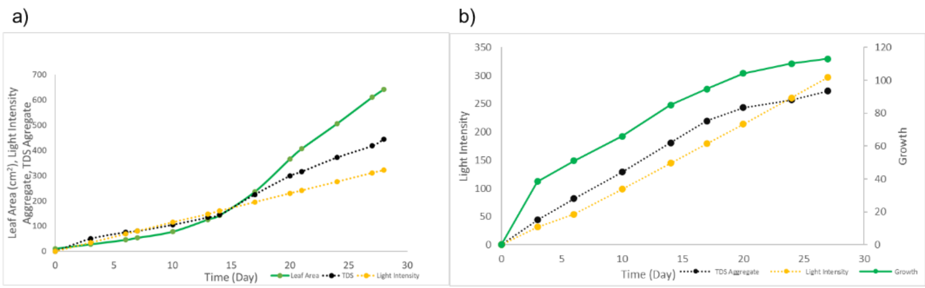

Figure 11 Aggregate graph of sensor data against time for (a) bok coy and (b) water spinach.

Plant growth is a process converting nutrients absorbed by the plants into carbohydrates by using solar energy through photosynthesis, as explained by Blankenship [21]. To see the effect of light intensity and TDS on growth, we used aggregation to convert light intensity into solar energy and TDS into nutrients absorbed by the plants. By definition, energy is the integral of power with respect to time, so we can find energy by simply calculating the area under the light intensity graph. Likewise, nutrients absorbed by plants can be calculated by the sum of the TDS graph.

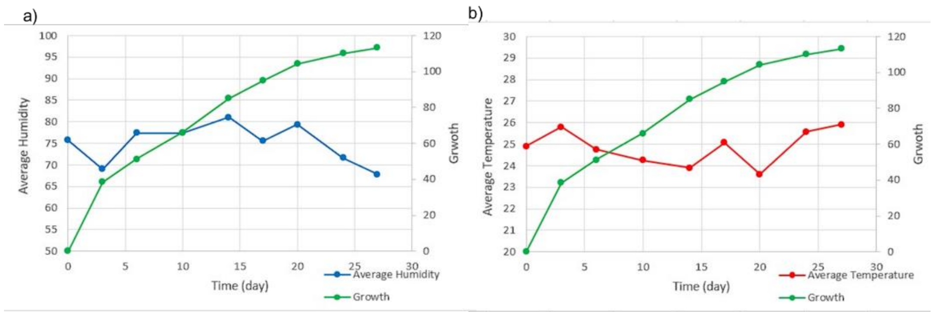

Figure 12 Aggregate graph of sensor data against time for water spinach: (a) average humidity, and (b) average temperature.

On both aggregate graphs in Figure 11, we can see that the light intensity aggregate has a linear form, indicating a relatively constant light intensity, while the TDS aggregate does not have a definite pattern because of the reason mentioned before. We can also see that in both plants, the growth pattern closely followed the TDS pattern. The aggregates were selected for light intensity and TDS because these two parameters directly affect the process of photosynthesis, while humidity and air temperature both indirectly affect the process of photosynthesis. In both graphs in Figure 12, we can see that for the water spinach, the growth pattern was unrelated to average humidity and average temperature pattern. The bok coy obtained the same results. This is because the temperature and humidity values did not change much, and the values were in the range of optimal temperature and humidity values required by bok coy and water spinach to grow, as given by Luckyardi *et al.* [22]. The optimal temperature and humidity for bok coy and water spinach growth is 25.4 °C to 31 °C and around 70 g/m^3, as given by Patil *et al.* [23].

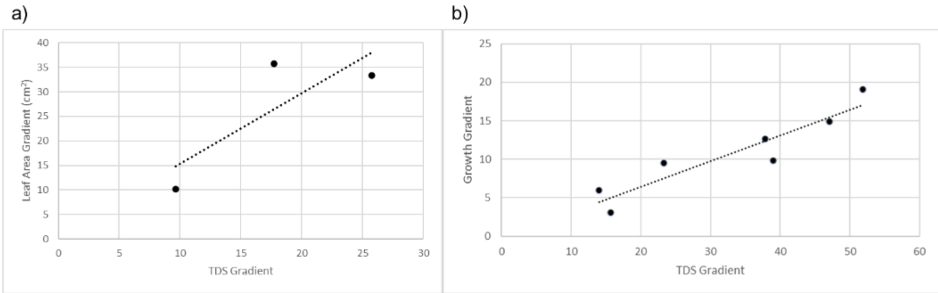

Figure 13 Gradient graph of (a) bok coy and (b) water spinach against TDS gradient.

Figure 13 shows the gradient graph made from the data in Figure 12. We can see that bok coy and water spinach growth was relatively proportional to the TDS gradient, meaning that the higher the TDS of the nutrient solution, the higher the plant growth. For bok coy and water spinach, the optimal TDS range is not less than 800, as given by Eridani *et al.* [24]. Hence, keeping the TDS at the upper value of that range will allow the plants to grow more optimally.

Table 1 Summary of machine learning results.

No	**Model**	**Average MAE (%)**	**Average R^2**
1	Linear Regression	12.69	0.746
2	Polynomial Regression	10.01	0.808
3	Random Forest Regression	8.3	0.933

From the data, a plant growth model was built. The dataset had a total of 18,000 rows and we used mean absolute error (MAE) and coefficient of determination (R^2) to evaluate the result. Table 1 shows a comparison of all three models. According to both average MEA and average R^2, the best model to use when building a plant growth model is random forest regression, with an average MAE of 8.3% (closer to 0%) and average R^2 of 0.93 (closer to 1) with a deviation of 2%.

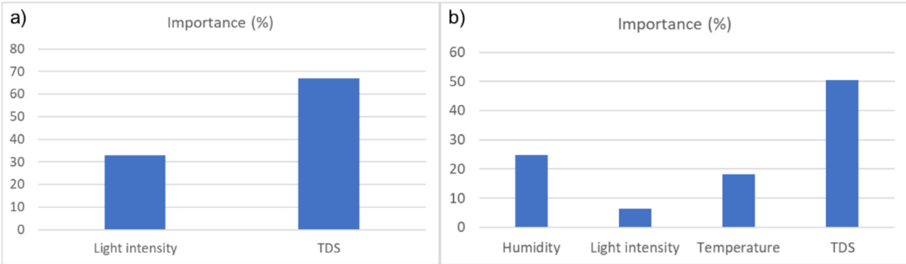

Figure 14 Feature importance for (a) bok coy and (b) water spinach using polynomial regression.

From the best model that was created (random forest regression), the feature importance value of each independent variable was reviewed to determine which variable affects growth. The difference in feature importance for bok coy and water spinach can be seen in Figure 14. This is due to water spinach being a semi-aquatic plant with many leaves and carbon fixation process type C3. Carbon fixation process type C3 cannot work properly if the temperature is too high and humidity is too low. This reduces photosynthesis ability, followed by stunted growth. This explains why humidity and air temperature have the highest importance after TDS (abiotic stress, acclimation, and adaptation in carbon fixation processes). From the model, we also found that TDS is more important than light intensity for plant growth. This is because, as explained, earlier light intensity stayed relatively constant throughout the research duration, which means that plant growth in this research was mostly affected by the change in TDS. Validation was performed on the measurement data for different harvest times. The results showed that all models can be used for predicting which parameters affect plant growth the most.

4 Conclusion

An IoT system capable of monitoring a commercial hydroponic system was successfully developed. The data gathered from the system were then used for further analysis using machine learning to create plant growth models using linear regression, polynomial regression, and random forest regression. Random forest regression produced the best result, according to its MAE and R^2 with a MAE of 8.3% (closer to 0%) and R^2 of 0.93 (closer to 1).

From the data and the model created using machine learning it was found that TDS affects growth the most, with TDS as the best parameter for control. According to the relationship between TDS gradient and plant growth gradient, the most optimal growth can be achieved by raising the TDS gradient or maintaining a high TDS at all times. This can be achieved by adding nutrient solution into the tank regularly. One solution for this is by integrating a control mechanism into the IoT system that was built. The control mechanism should be able to use the TDS data to then add or stop adding nutrients to the tank automatically.

5 Acknowledgements

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