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Yield Evaluation of *Brassica rapa*, *Lactuca sativa*, and *Brassica integrifolia* Using Image Processing in an IoT-Based Aquaponics with Temperature-Controlled Greenhouse

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ABSTRACT

The paper introduced the development of a self-sustainable smart aquaponics system in a temperature-controlled greenhouse with a monitoring and automatic correction system using an Android device through the Internet of Things (IoT) and plant growth monitoring system through image processing using Raspberry Pi. The system involves the acquiring of real-time data detected by the light intensity sensor, and air temperature and humidity sensor. It also includes the monitoring of the pH level and temperature of the recirculating water of the system. If the acquired data is not within the threshold range, the correcting devices, namely grow lights, exhaust and inlet fans, evaporative cooler, aerator, and peristaltic buffer device were automatically triggered by the system to correct and achieve its normal status. The internet remote access includes the effective wireless transmission and reception of data reports between the system and an Android unit with the Android application in real-time. The study focused on the evaluation of two experimental set-ups comparing the plant growth between conventional soil-based farming and the smart aquaponics system using image processing. After data gathering, results showed that the smart aquaponics set-up successfully produced a yield better than the conventional farming set-up.

INTRODUCTION

Among the effects of inefficient agricultural methods such as environmental degradation caused by waste from conventional farming, disruption of food supplies from weather volatility, and wasteful energy usage, the agricultural practices seek innovative, sustainable, and economically viable solutions. As a response to these problems, aquaponics is the combination of aquaculture, breeding, and raising of an aquatic organism such as fish, shrimps, crabs in a controlled environment; and hydroponics, production of the plant in a soilless medium, in a mutually beneficial environment. In recirculating aquaculture, nutrients, which are wastes eliminated directly by the fish or produced by microbial breakdown of organic wastes, are absorbed by plants cultivated hydroponically (Amado, Valenzuela, & Orillo, 2016; Chapae, Songsri, & Jongrungklang, 2019; Rakocy, Bailey, Shultz, & Thoman, 2004; Rakocy, 2012; Sace & Fitzsimmons, 2013; Salamah, Fadilah, Khoiriyah, & Hendrayanti, 2019; Somerville, Cohen, Pantanella, Stankus, & Lovatelli, 2014; Tolentino et al., 2017; Tolentino et al., 2019).

Aquaponics gives more security on food loss, more productivity in relation to its cost, and more accessibility as it can be placed on urban areas. Although different studies about aquaponics have

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improved locally and internationally, most of them are having problems such as lack of constant monitoring of the sensing system with corresponding correcting devices, insufficient information to the aquaponics enthusiast on the status of the plants' growth, unsuitable climate for specific crops that need lower temperature requirements, and destructive methods of measuring plants (De Belen & Cruz, 2017; Galido et al., 2019; Murad, Harun, Mohyar, Sapawi, & Ten, 2017; Nagayo, Mendoza, Vega, Al Izki, & Jamisola, 2017; Tai et al., 2017; Tolentino et al., 2017).

Traditional direct measurement methods of plant growth are normally easier but take a lot of time and are damaging to plants. As an important problem to be answered in plant studies, the plant feature measurement which was proposed by Yeh et al. (2014) has beneficial applications especially in plant growth modeling and climate control in greenhouses.

A system developed by Tai et al. (2017) was greatly associated with environmental parameters where MG82FG5B32 Developer Edition in MEGAWIN Technologies was used as a microcontroller. A database was created with MySQL for the human-machine interface through the website. This study only focused on air temperature, air humidity, soil moisture, and illumination. De Belen & Cruz (2017) developed an aquaculture system that uses three parameters namely: pH, temperature, and flow rate. These three parameters' correlation was computed, and experiments showed that "the pH has inversely proportional to temperature, but flow rate has no effect on the pH and temperature". In Nagayo, Mendoza, Vega, Al Izki, & Jamisola (2017), an aquaponics system with the water recirculation system, aquaponics control, and monitoring system using Arduino, GSM shield, and NI LabVIEW, solar energy conversion system, and cooling and heating systems was designed for plant and fish growth. Meanwhile, in Galido et al. (2019), their aquaponics system utilized an Ion Sensitive Field Effect Transistor (ISFET) as a pH sensor for optimum growth of plants and fishes. The superiority and efficiency of the ISFET-based pH sensor over the commonly used glass electrode pH sensor were proven through various experiments and testing its performance for evaluation. An aquaponics system that was proposed in Murad, Harun, Mohyar, Sapawi, & Ten (2017) was developed that used temperature sensor, pH sensor, water sensor, servo, peristaltic pump, solar, liquid crystal displays (LCD), and GSM module water monitoring of aquaponics. The data is displayed through LCD and a notification is sent via GSM module. Meanwhile, wireless sensor networks which use Raspberry Pi 3 were developed for a greenhouse that monitors the temperature, humidity, and soil moisture (Anire, Cruz, & Agulto, 2017) and for a lettuce growth chamber that monitors light intensity, temperature, and humidity (Cabaccan, Cruz, & Agulto, 2017). In Jorda Jr et al. (2019), the development and innovation of an IoT-based micro-farm prototype were proposed. The system created involves the detection of light intensity, soil moisture, and temperature through the use of various sensors that were connected to the Arduino microcontroller. A computer vision-based canopy area measurement system for lettuce was developed by Calangian et al. (2018) using an image processing algorithm. Lastly, machine vision and image processing techniques were implemented by de Luna, Dadios, Bandala, & Vicerra (2020) for tomato plant growth evaluation and tomato's fruit and flower detection.

None of the existing aquaponics systems have considered monitoring of pH level, light intensity, water, and air temperature, and indirect measuring of plant area or canopy area through image processing, as well as remote monitoring through the Internet of Things (IoT), to be integrated all together. Monitoring and automated correction of these environments and water parameters can lead to optimized crop and fish growth of an aquaponics system. The stated parameters and features are what this study proposes to attain.

The general objective of this study is to develop a temperature-controlled greenhouse and plant growth monitoring system of smart aquaponics through the Android IoT application. Specifically, this research aimed to develop a Python program on Raspberry Pi that processes the acquired images from the camera to monitor and assess the plant-based on the surface area using image processing and to compare the growth of the plants (surface area of the leaf) which are grown in the conventional soil-based farming with the proposed smart aquaponics system using the developed Python-based image processing program. The study is a self-sustainable smart aquaponics system that will use solar power, hence lessens electrical consumption while securing food in urban zones that has minimal space and increasing sustainability. The system will utilize recirculating water and soilless medium, therefore minimizes the use of water resources, disregards the demand of chemical fertilizers, and guarantees high yields of fresh, purely organic, nutritious, and easy to harvest. The implementation of a plant growth monitoring system shall eliminate the problems regarding the traditional contact method of measuring that may lead to the destruction of plants. Maintaining a temperature suitable crops solves the unsuitability of growing these crops on a warm urban area. On Android application of a common smartphone, the water parameter readings, specifically, pH value, water temperature, light intensity, and air temperature readings, as well as the data from the growth measurement of plants, can be displayed that allows the urban farmers to remotely monitor their aquaponics system through the Internet of Things gateway.

The system focuses on monitoring and automatic correcting the light intensity, air temperature, pH level, and water temperature. In the plant growth monitoring system, the study is limited to the measurement of the estimated surface area of the plants by top view image capturing. To monitor the plants, the entire planting beds shall be captured repeatedly every week. The study is limited to culturing Pak Choi/Pechay Tagalog (*Brassica rapa*), Lettuce/Letsugas (*Lactuca sativa*), Mustard Greens/Mustasa (*Brassica integrifolia*), and Nile Tilapia (*Oreochromis niloticus*). Also, it is limited in comparing the plant growth of the smart aquaponics from conventional soil-based farming.

MATERIALS AND METHODS

Research Design

The study was conducted in January 2018 at the City Cooperative Development Office's Aquaponics Setup located in Pasay City, Philippines. It focused on comparing the yield of the experimental A, conventional farming, and the experimental B, the aquaponics system. The schematic diagram of the two experimental set-ups is shown in Fig. 1. The conventional farming set-up is composed of the plants grown with a soil medium in Styrofoam containers. The growth is monitored by a manual image capturing of each plant using a web camera connected to the Raspberry Pi module. The acquired images undergo image processing to obtain the surface areas of the plants.

The aquaponics system is composed of five sections namely the water parameter detection and correction, environment parameter detection and correction, automated feeding, plant growth monitoring system, and internet remote access. The block diagram of the proposed aquaponics system is shown in Fig. 2.

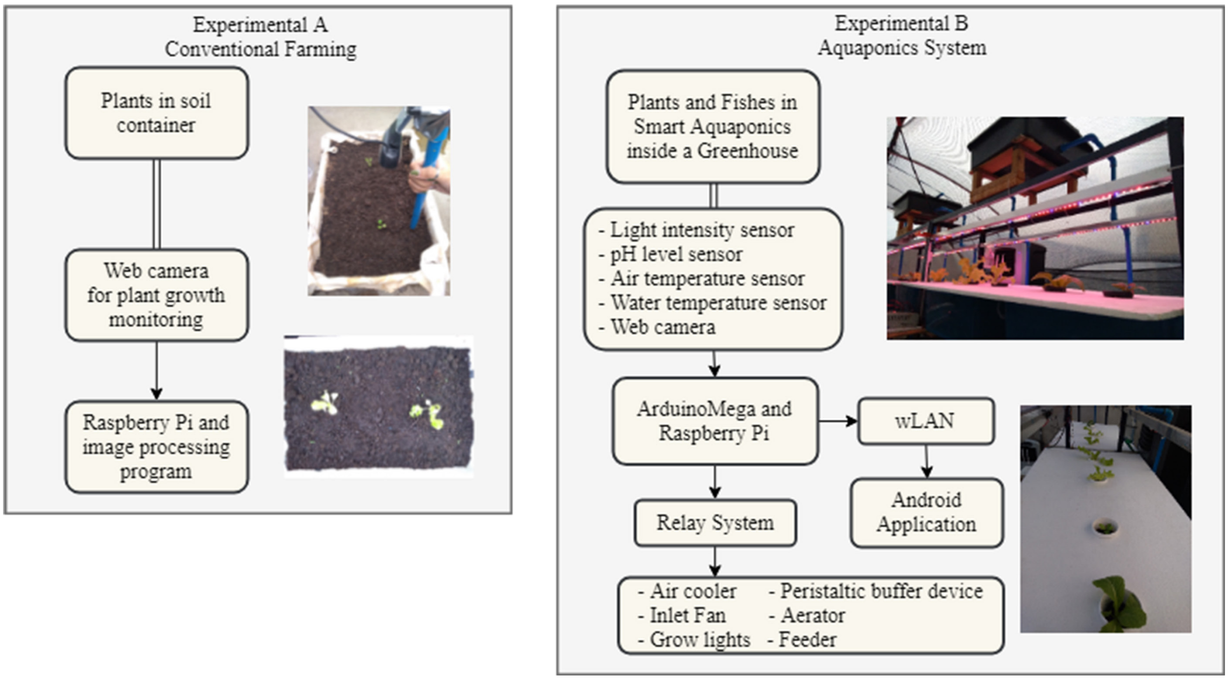


Fig. 1. Schematic Diagram of Experimental A and B

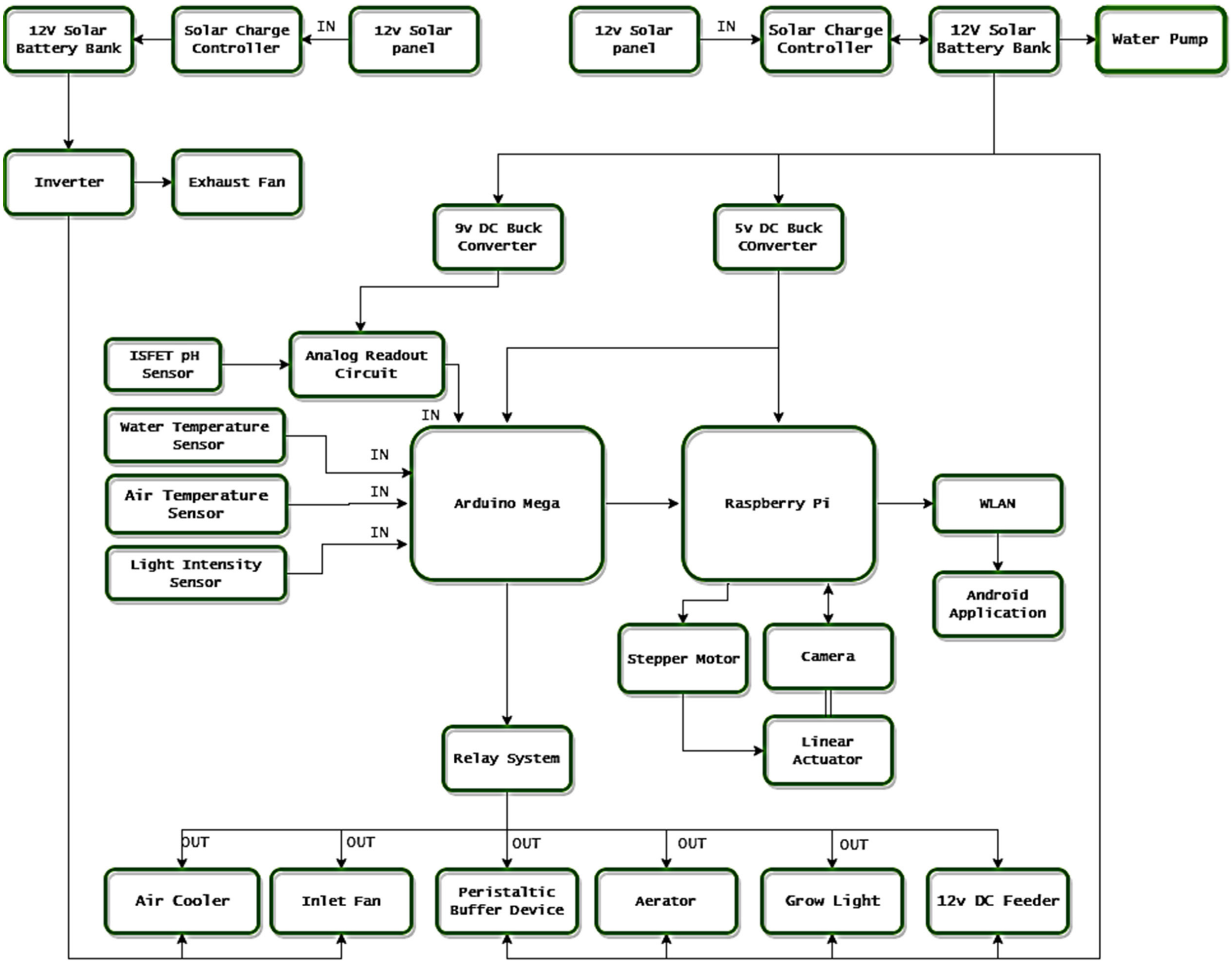


Fig. 2. Block diagram of the smart aquaponics system

Fig. 3 shows how the water parameters are controlled in the aquaponics system. The water parameter of the aquaponics system such as pH level and the water temperature was monitored and controlled to achieve optimum growth of the plants in the grow bed and fishes in the tank. Each sensor connected to the Arduino Mega was set with threshold values to sustain the best growth of tilapia in the fish tank, and pak choi, lettuce and mustard greens in grow beds. Both water parameters were monitored and recorded every second. The water's acidity and alkalinity were measured by the pH sensor. The pH sensor used is the Ion Sensitive Field-Effect Transistor or ISFET. The ISFET pH sensor is first to be sent to the analog readout circuit (ARC) for voltage amplification and then be sent to the Arduino Mega for data processing. Tilapia can tolerate a wide pH range which is pH 5.0 - 10.0 while plants prefer pH < 6.5 (Thorarinsdottir, 2015). When water pH is between 7.5 and 8, nitrification at its best will be achieved. Moreover, A pH lower than 5 or above 8 places a risk on the living groups present in the aquaponics system and is an utmost concern (Robinson, 2014; Savidov, Hutchings, & Rakocy, 2007; Somerville, Cohen, Pantanella, Stankus, & Lovatelli, 2014; Tolentino et al., 2017; Tyson, Simonne, Treadwell, White, & Simonne, 2008). Based on these conditions, the threshold range for the pH level for the system was from 6 to 8. If the pH < 6, the peristaltic buffer pump automatically released calcium carbonate ($CaCO_3$) to add base and increase the pH slowly until the readings return at the normal pH range. If the pH < 8, the pump will release water to decrease the pH inside the tank.

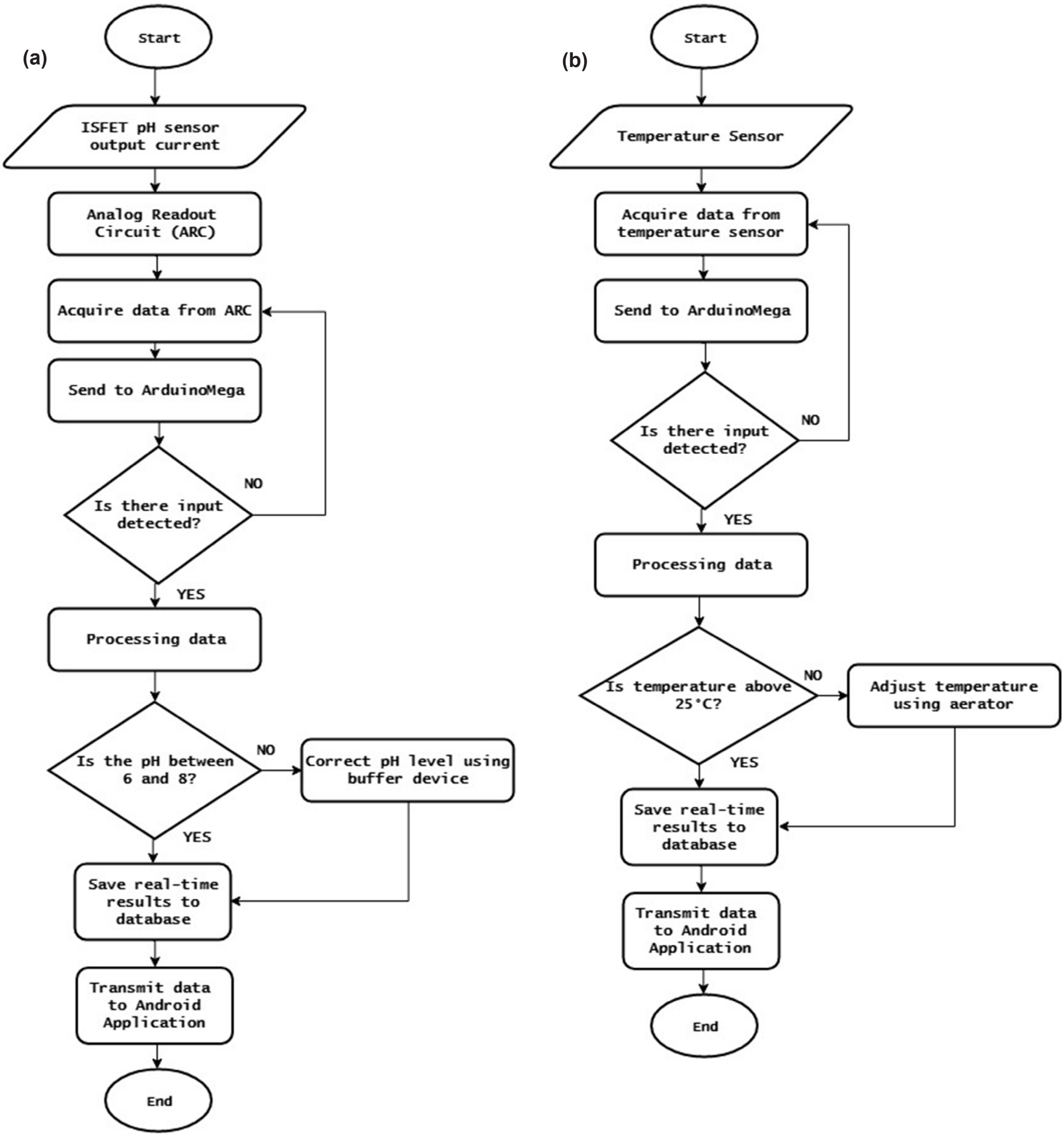


Fig. 3. Flowchart of the controlling of water parameters: (a) pH and (b) temperature

The temperature sensor used for the recirculating water is the DS18B20 digital thermometer that provides Celsius temperature measurements. In aquaponics, optimal growth of tilapia was observed in water temperatures ranging from 22 to 29°C (Mjoun, Rosentrater, & Brown, 2010; Robinson, 2014; Somerville, Cohen, Pantanella, Stankus, & Lovatelli, 2014; Tolentino et al., 2017). For this study, the water temperature, Twater, was set at 25°C which is in the middle of the optimal temperature range of tilapia. If the Twater > 25°C, the aerator was automatically turned on to supply oxygen to the fish. Water temperature affects the capacity of water to hold dissolved oxygen.

Coldwater at high atmospheric pressure holds more dissolved oxygen than warm water at low atmospheric pressure. If Twater < 25°C, the aerator was automatically stopped. Correcting devices such as peristaltic buffer device, and aerator was executed when parameters were monitored at critical values and triggered through a relay system as shown in Fig. 4.

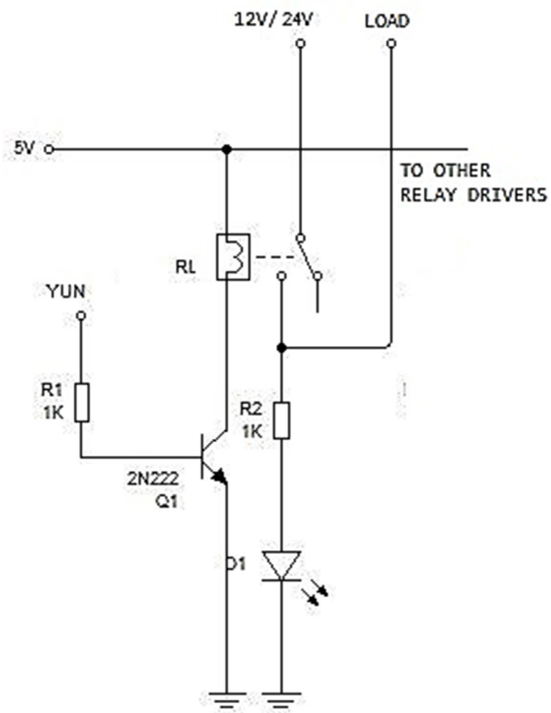


Fig. 4. Relay system

The environment parameters inside the greenhouse namely light intensity, the air temperature was monitored and controlled to achieve a favorable rate of plant production. Each sensor connected to the Arduino Mega was set with threshold values. The sensor used to measure the air temperature for the greenhouse is DHT11 sensor. The temperature of the air was measured by degrees Celsius. The suitable temperature range for most vegetables is 18–30°C (Somerville, Cohen, Pantanella, Stankus, & Lovatelli, 2014). For this study, the air temperature, Tair, was set at 25°C which is in between the suitable temperature range. If the Tair was > 25°C, the evaporative air cooler was automatically turned on. If the Tair < 25°C, the inlet fan was automatically turned on which lets the cool air inside the greenhouse. If the Tair = 25°C, both the cooler and the inlet fan were automatically turned off.

Grow lights were included in the aquaponics system so that it will act as artificial light to supply the illumination needed by plants for growth processes and photosynthesis during nighttime. Based on studies of Crowley, Molina, & Burgess (2015), Kung et al. (2011), and Muhamad (2015), also this research measurements using a lux meter, the intensity of natural light during sunrise or sunset is in the range of 300-500 lx or typically about 400 lx. For this reason, the grow lights will be operated when the light intensity is below 500 lx. A BH1750FVI light intensity sensor was utilized to measure the illumination for the plant grow beds. Correcting devices such as inlet fans, air coolers, and grow lights were executed when parameters were monitored at critical values using a relay system.

The automatic feeder was created for the operation of food dispensing to the fish. It was programmed with an initialized default time setting in the Arduino Mega that was turned on every 8 hours. The operation happens when the microcontroller sends a digital signal to the relay driver for a feeder to dispense food.

Plant growth monitoring system was composed of image processing wherein the images of plants were captured by the camera connected to a linear actuator that was responsible for camera movement from the first plant to the next plant. The captured images underwent image enhancement, image segmentation, and dimension acquirement using a Python program in a Raspberry Pi module. The projected area acquired from the image processing was transmitted to the database and the Android application for data visualization. The Python IDE was used for the image processing of the acquired plant images from the camera and controls the movement of the linear actuator that was synched with the capturing of the camera in every plant. The block diagram of the system is shown in Fig. 5.

Fig. 6 shows the linear actuator which was created for the plant growth monitoring system. The cameras used in the growth monitoring system were connected to a linear actuator that manipulated the movement of the camera. The linear actuator was primarily composed of an aluminum rod, stepper motor, and a conveyor belt.

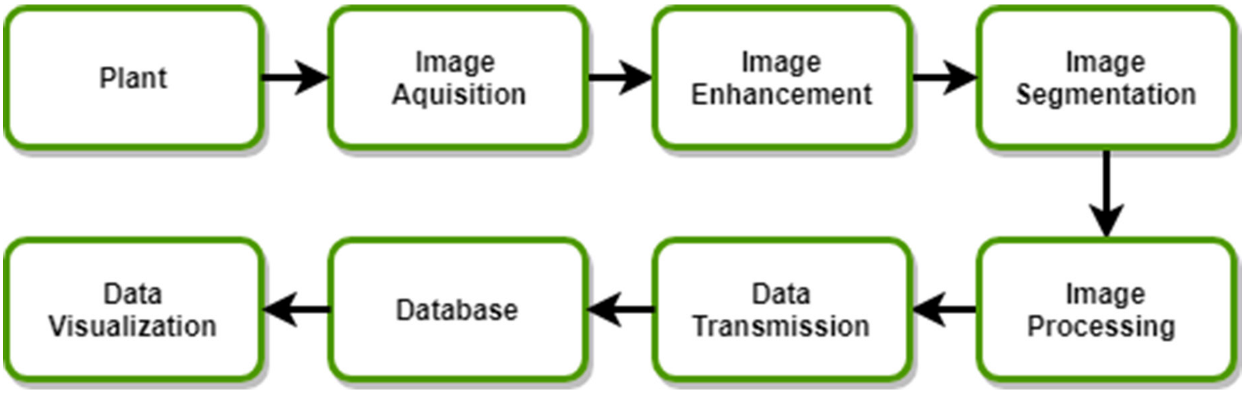
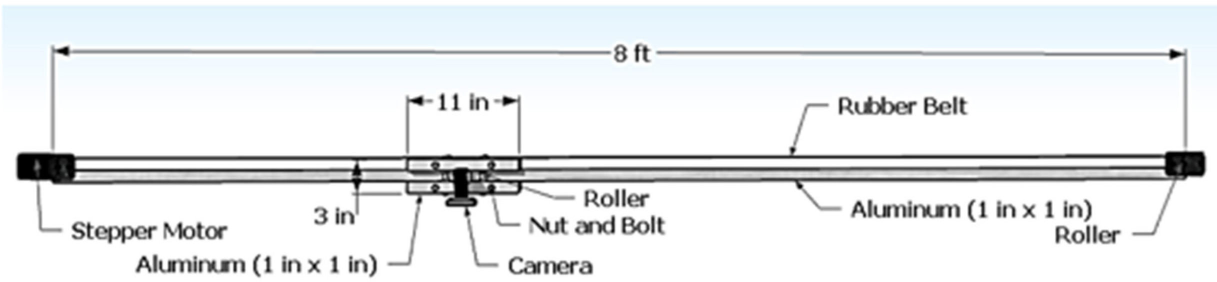
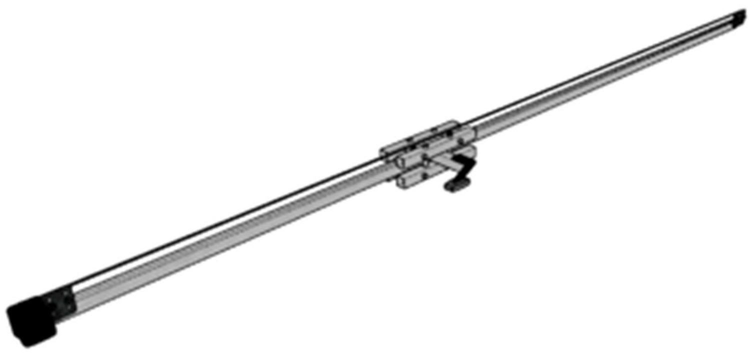


Fig. 5. Image processing of plant growth monitoring system



(a)



(b)

Fig. 6. (a) Linear actuator's dimensions and (b) its isometric view

Fig. 7 shows the image capturing process of a web camera mounted to the linear actuator. The image acquisition programmed using Python IDE was the initial process of plant growth monitoring before it undergoes image processing. Fig. 8.a. shows the sample captured the image of the plant. The camera movement atop one plant to another was controlled by the linear actuator. In the event when all of the plants were captured, the linear actuator moved the camera back to its initial position. The same process was programmed to happen every 1 week.

A program was developed for image processing. Fig. 8.b. shows the image enhancement contained the process of separating the foreground of the image from the background through image morphing. RGB (red-green-blue) values were converted to L*a*b values then a threshold range of color green was set to be identified on the image. Through image morphing using erosion and dilation, the image was contoured and structured. The boundaries of the foreground object were eroded, the size of the foreground object increased, and the gaps were closed. Fig. 8.c. shows the image segmentation; a black and white image was formed through binarization. The white image acted as the plant area and the black color represented the background. The number of pixels were counted and underwent pixel to centimeter squared conversion.

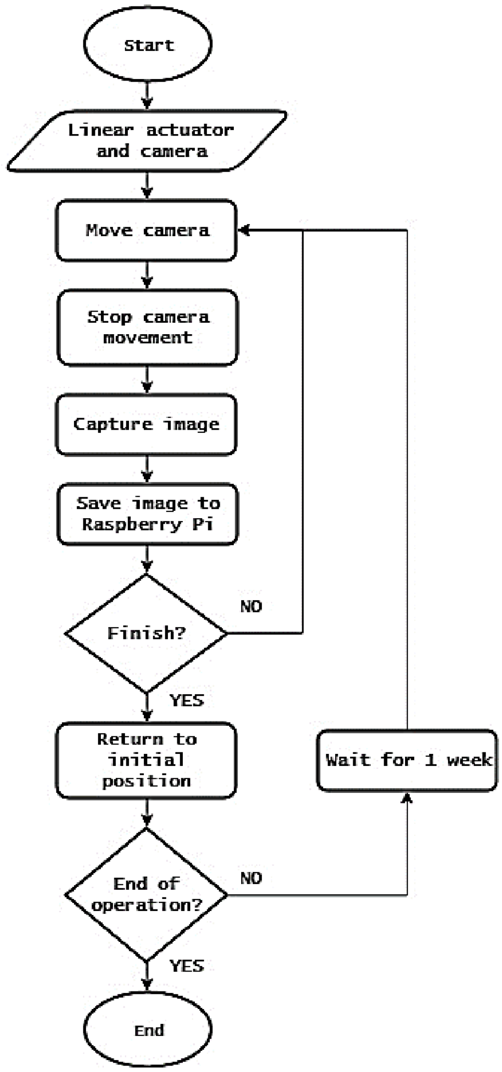
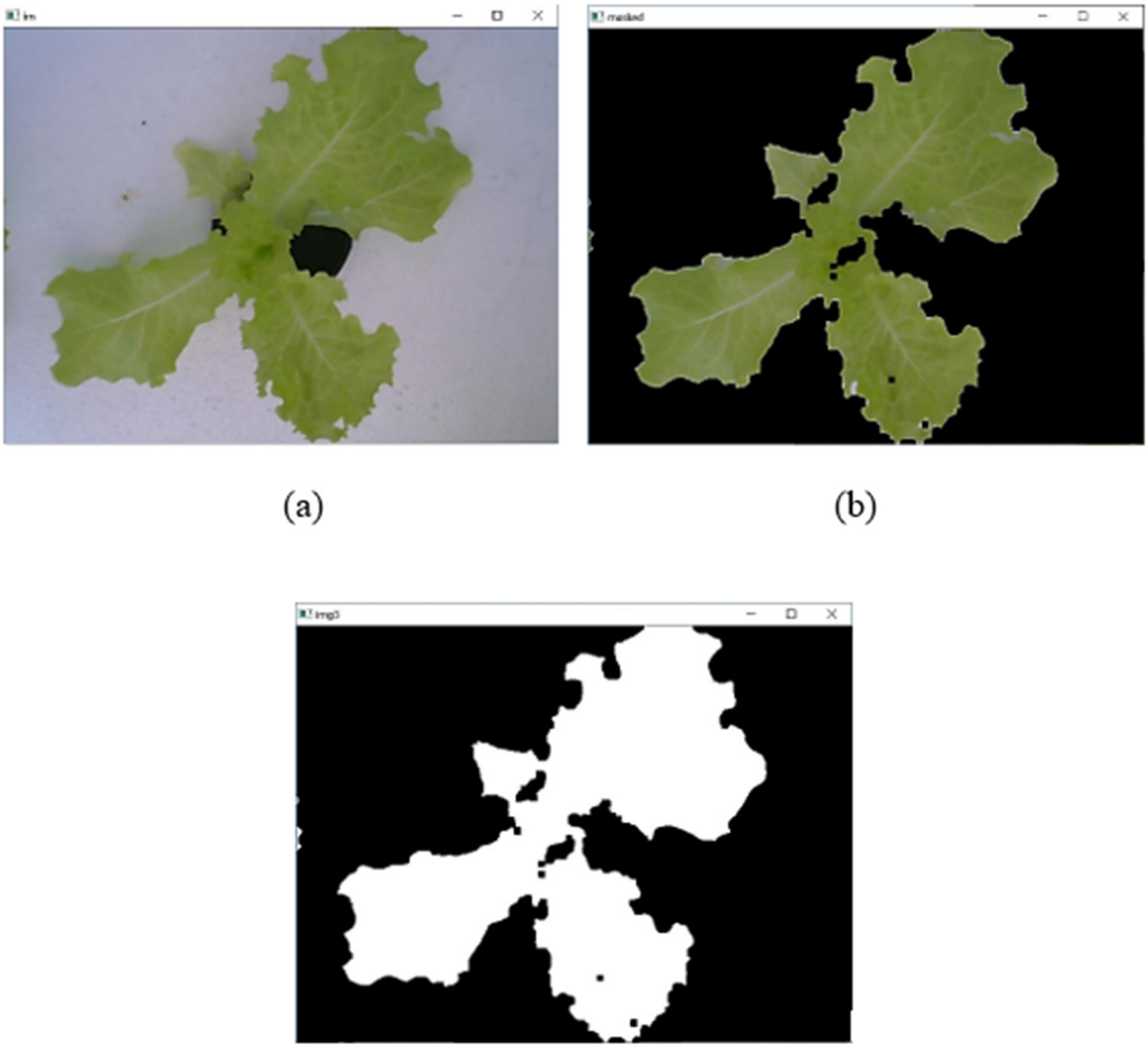


Fig. 7. System flowchart for plant image capturing



(a) (b)

(c)

Fig. 8. Image processing of the proposed plant growth monitoring system

The internet remote access includes the transmission and reception of data reports between the system and the Android application. The output obtained from the parameter detection and its analysis on Arduino Mega as well as the data acquired from the plant growth monitoring system are transmitted by the Raspberry Pi and are stored in the database. The values are visualized in an Android unit through the graphical user interface of the AquaDroid Version 2.0 Application. The MIT App inventor IDE was used for developing the AquaDroid V2.0 Android Application which served as the GUI of the system. Fig. 9 shows the Android application.

The Greenhouse and the Aquaponics Set-up

The greenhouse used in the system has a dimension of 10 x 15 x 8 feet. It was constructed with aluminum framing and polyethylene sheets. Attached were the inlet fans at the top of the greenhouse door and the exhaust fan at the far end of the greenhouse. In between the two inlet fans is the air temperature sensor. The greenhouse design is shown in Fig. 10.

Fig. 9. AquaDroid V2.0 application retrieved data UI

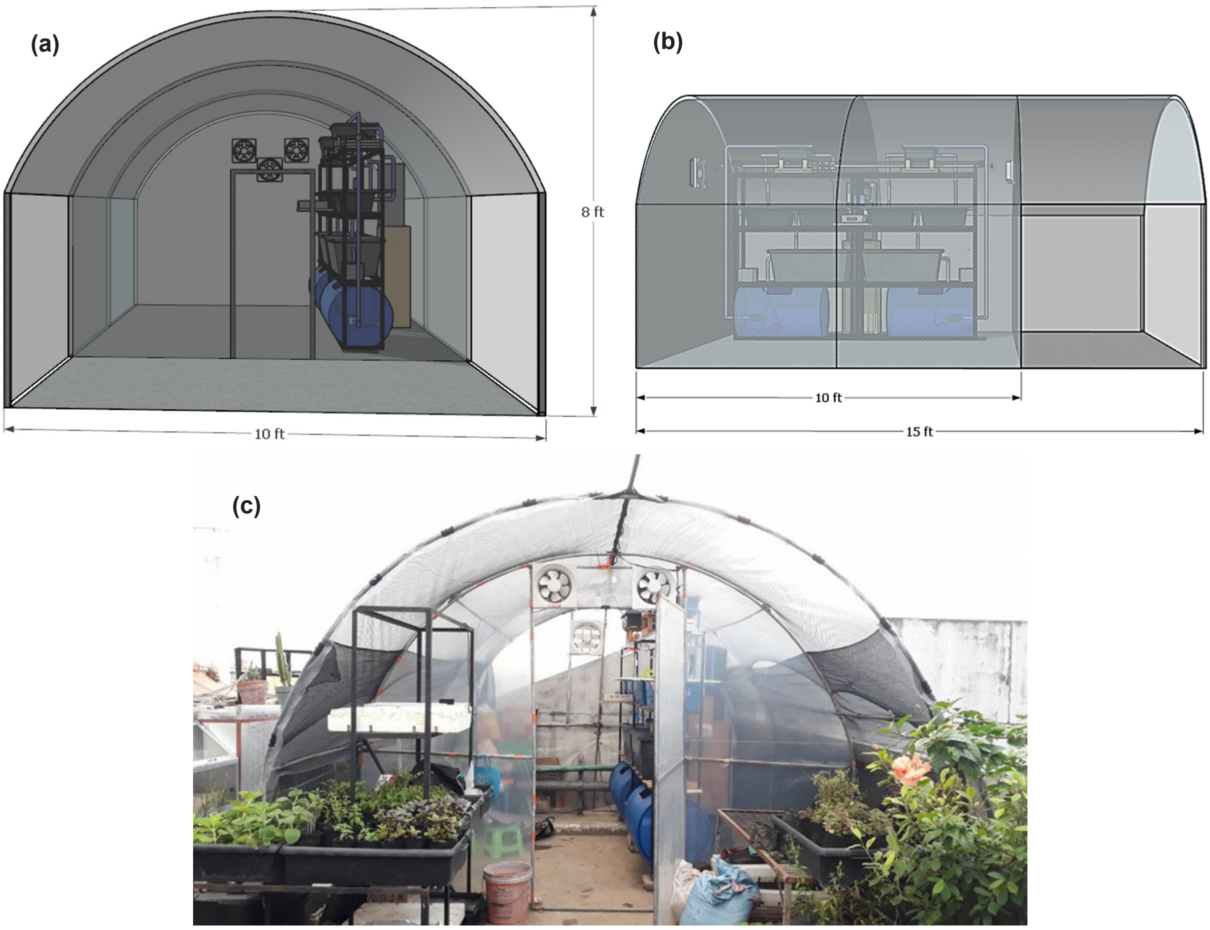


Fig. 10. The greenhouse where the smart aquaponics was located: (a) front view, (b) side view design of greenhouse with dimensions and the (c) actual greenhouse

The parts of a single set-up of the smart aquaponics are shown in Fig. 11. The trellis of the set-up primarily contained a filter, two grow beds, a sump tank, and a fish tank. At the top of the grow beds where the grow lights and the linear actuator with a web camera were fixed on the trellis. The sump tank contained the ISFET sensor. The peristaltic buffer device was connected to the sump tank through a hose where the $CaCO_3$ was being released. At the top of the fish tank are the automatic feeder that drops food for the fishes, and the aerator correcting device that had its hose submerged in the fish tank's water. The fish tank also contained the water temperature sensor inside. The whole set-up was powered by two 265 W solar panels and three 120 W solar panels as shown in Fig. 12.

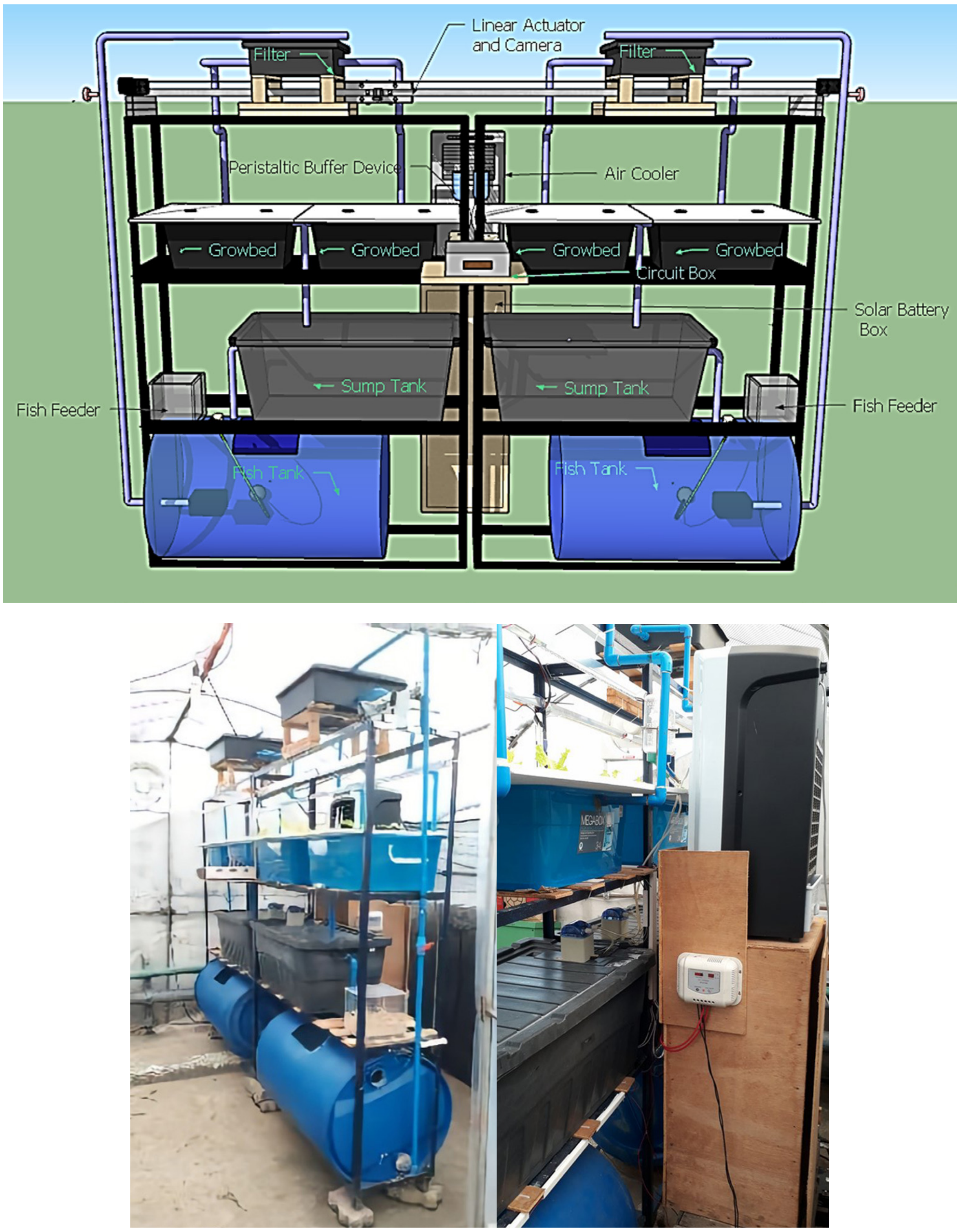


Fig. 11. The smart aquaponics set-up: (a) the aquaponics design with dimensions, (b) the actual smart aquaponics

Fig. 12. Solar panels

Evaluation Procedure

The light intensity of the illumination of the plants was tested by using the BH1750FVI light intensity sensor within 20 trials. The temperature level was evaluated using a standard digital light meter as the reference for data accuracy. Within 20 trials, the air temperature inside the greenhouse was also tested by using the DHT11 sensor. The temperature level was evaluated using a standard digital thermometer as its reference for data accuracy. The plant growth monitoring system was also evaluated by assessing the accuracy of the Python image processing program. Under 20 image samples, the program was compared to Easy Leaf Area Software (Easlon & Bloom, 2014) which is a tool that rapidly and accurately measures leaf area in digital images in seconds. All evaluations were done by using t-tests with a 0.01 level of significance.

RESULTS AND DISCUSSION

Python Image Processing Evaluation

To test the acceptability of the Python Image Processing Program used in the plant growth monitoring system, a comparison was done with software that provides an accurate, free and rapid tool to estimate leaf area from digital images. Twenty sample plant images were processed to both Python Image Processing Program and Easy Leaf software (Easlon & Bloom, 2014). The surface area measurements from the Python image processing program were compared with the measurements the Easy Leaf Area software as shown in Fig. 13.

The surface areas attained underwent statistical testing to determine the accuracy of the Python image processing program. Using a student's t-test or independent two-sample t-test assuming equal variances and assuming unequal variances (Table 1, Table 2, and Table 3), the acceptability of the Python image processing program was evaluated. For the following hypotheses for this study, the null hypothesis indicates there is no significant difference between the Python image processing program and the Easy Leaf Area software. The level of significance was set to 0.01.

In summary, as shown in Table 1, the Python image processing program and Easy Leaf Area software were compared. The ρ – value is greater than 0.01 which means that there is no statistical difference between the means of the surface area acquired from the Python image processing program and Easy Leaf Area software. This signifies that the Python image processing program is acceptable for its accuracy.

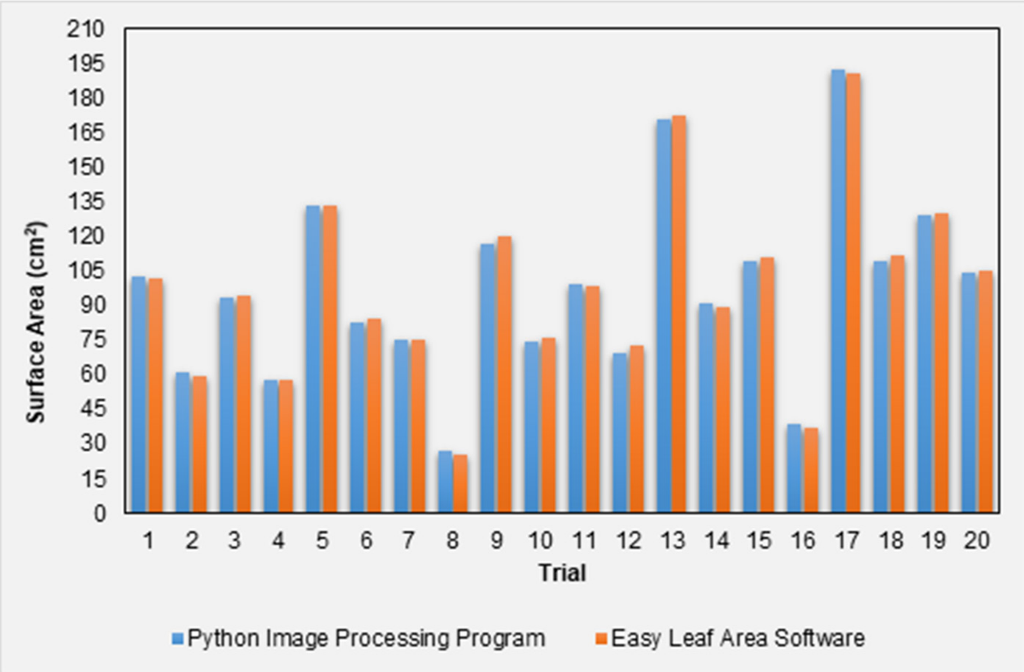


Fig. 13. Python Image Processing Program vs Easy Leaf Area Software

Table 1. Student's t-test for image processing: Summary

Groups	Count	Hyp Mean Diff		0
		Mean	Variance	Cohen d
Python Image Processing Program	20	96.862	1617.038	
Easy Leaf Area Software	20	97.321	1644.763	
Pooled			1630.901	0.011366

Table 2. Student's t-test for image processing: Equal variances

t-test	std err	t-stat	df	ρ – value	t-crit	lower	upper	Alpha	0.01
								sig	effect r
One-Tail	12.7707	0.03594	38	0.48576	2.42857			No	0.00583
Two-tail	12.7707	0.03594	38	0.97152	2.71156	-35.0874	34.1694	No	0.00583

Table 3. Student's t-test for image processing: Unequal variances

t-test	std err	t-stat	df	ρ – value	t-crit	lower	upper	Alpha	0.01
								sig	effect r
One-Tail	12.7707	0.03594	38	0.48576	2.42858			No	0.005831
Two-tail	12.7707	0.03594	38	0.97152	2.71157	-35.0875	34.1695	No	0.005831

Comparison of Surface Area of Plants between Aquaponics System and Conventional Soil-based Farming

For the aquaponics set-up, the pak choi plants started as seeds grown in a Styrofoam box to become seedlings. The seedlings were transferred from the box to grow beds after three weeks. For the conventional soil-based farming, pak choi seeds were directly planted to a Styrofoam box filled with soil and remained for plant growth monitoring. For the two different experimental set-ups, the surface area of each plant was measured using the proposed vision-based plant growth monitoring of the system through image processing as shown in Table 4. Plant measuring was done every week within three weeks and the average area of each test system was calculated to see their significant differences.

For the aquaponics set-up, the lettuce plants started as seeds grown in a Styrofoam box to become seedlings. After three weeks, the seedlings were ready to be transplanted from the box to grow beds. For the conventional soil-based farming, lettuce seeds were directly planted to a Styrofoam box filled with soil and remained for plant growth monitoring. In all set-ups, the surface area of each plant was measured using vision-based plant growth monitoring of the system through image processing. Plant measuring was done every week within three weeks and the average area of all the lettuce plants each test system was calculated to see their significant differences as shown in Table 5.

Table 6 shows the comparison of the measurements from the Aquaponics system and Conventional farming for the mustard greens. For the aquaponics set-up, the mustard greens were planted in a Styrofoam box to become seedlings. When the seedlings were ready for transplanting after three weeks, seedlings were transferred from the box to grow beds. For the conventional soil-based farming, mustard seeds were directly planted to a Styrofoam box filled with soil and remained for plant growth monitoring. The surface area of each plant on both set-ups was measured using vision-based plant growth monitoring of the system through image processing. Within three weeks, plant measuring was done every week as shown in Fig. 14. To see their significant differences, the average area of each set-up was calculated.

Table 4. Average surface area of pak choi grown in aquaponics system and conventional soil-based farming every week

Day Lapsed	Area (cm^2)	
	Proposed Aquaponics System	**Conventional Farming**
21	81.64	4.49
28	95.75	4.85
35	150.61	7.49

Table 5. Average surface area of lettuce grown in aquaponics system and conventional soil-based farming every week

Day Lapsed	Area (cm^2)	
	Proposed Aquaponics System	**Conventional Farming**
21	91.70	10.27
28	107.52	13.61
35	151.20	30.94

Table 6. Average surface area of mustard greens grown in aquaponics system and conventional soil-based farming every week

Day Lapsed	Area (cm^2)	
	Proposed Aquaponics System	**Conventional Farming**
21	51.45	7.6
28	73.71	9.18
35	97.86	10.79

It was observed that the mustard greens, pak choi, and lettuces which are grown in the proposed smart aquaponics system had the greater growth than the mustard greens, pak choi, and lettuces which are planted using conventional soil-based farming as shown in Fig. 14, Fig. 15, and Fig. 16, respectively.

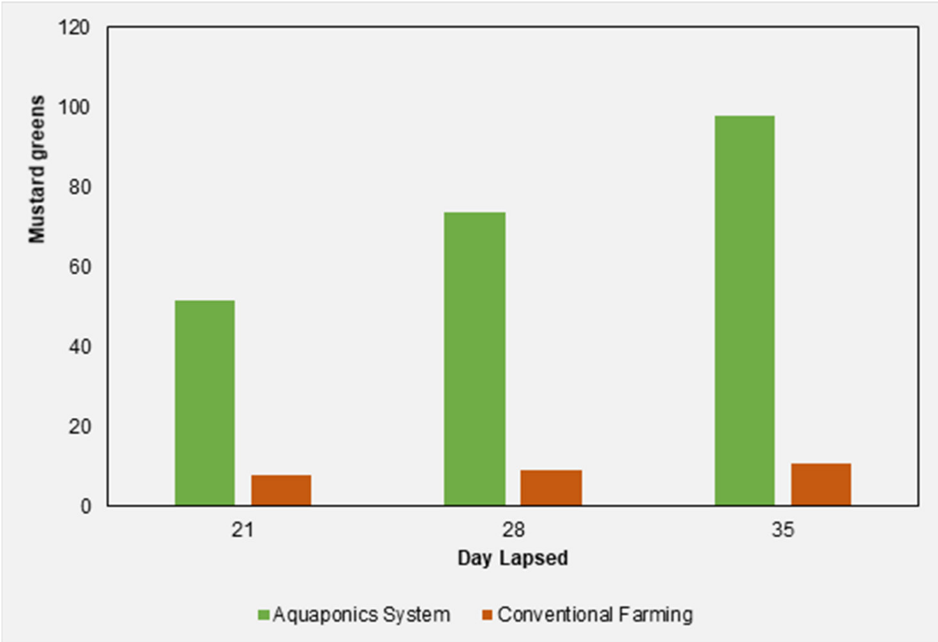


Fig. 14. Surface area of mustard greens for the two set-ups

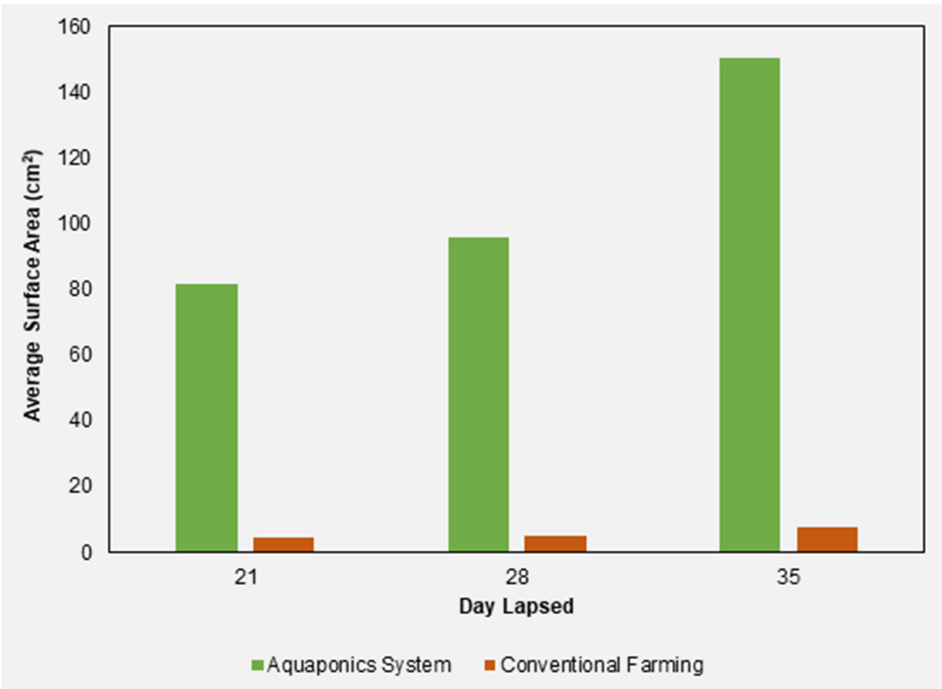


Fig. 15. Surface area of pak choi for the two experimental set-ups

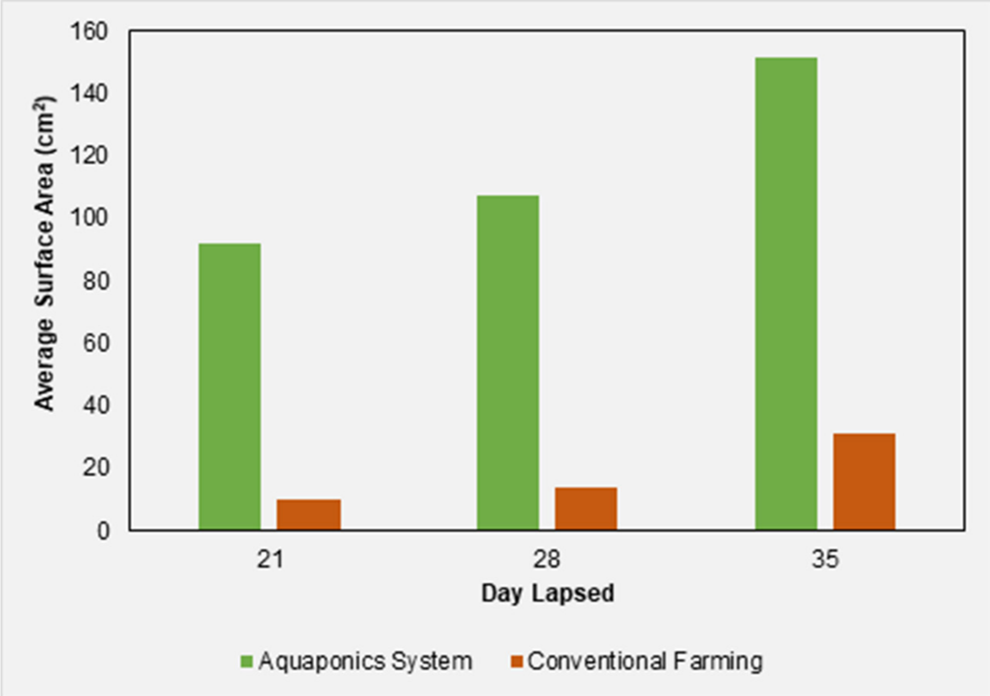


Fig. 16. Surface area of lettuce for the two set-ups

CONCLUSION

The proposed Python-based image processing program and the Easy Leaf Area Software showed no statistically significant difference in its accuracy in measuring plant area. The Python program successfully acquired the plant area through image processing. The lettuce, mustard greens, and pak choi which were grown in the smart aquaponics system presented significantly greater growth compared to those that were grown in conventional soil-based farming. Thus, the proposed smart aquaponics system is an effective urban farming scheme of remotely growing vegetables faster. Future studies include the growth monitoring of the fish in the fish tank using image processing, determination of the suitable amount of light intensity of the grow lights that can enable the plants to grow at maximum or optimum level, and detection of plant diseases in aquaponics system using image processing.

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