CHEMICAL ENGINEERING TRANSACTIONS

VOL. 112, 2024

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Selena Sironi, Laura Capelli

ISBN 979-12-81206-13-7; **ISSN** 2283-9216

DOI: 10.3303/CET24112048

Smart Hydroponic Plant Growth Chamber with Integrated Air Conditioning System, Artificial Photosynthetic Lighting System, and Smart Monitoring System

Carlo Jay Ayupan[a,*], Cristian Carl Fernandes[a], Vince Harrison Balfermoso[a], Alexander Hamilton S. Atienza[b]

[a]College of Engineering and Architecture, Mapua Malayan Colleges Mindanao, Gen. Douglas MacArthur Hwy, Talomo, Davao City, 8000 Davao del Sur, Philippines
[b]Mapua Institute of Technology at Laguna, Mapua Malayan Colleges Laguna, Pulo-Diezmo Road, Cabuyao, 4025 Laguna, Philippine
ahsatienza@mcm.edu.ph

Given the escalating population in the Philippines, enhancing food security and establishing a community free from hunger is paramount. It is essential for the development of a more food-sustainable nation. Although modern agriculture meets current demands through mechanization and synthetic inputs, it fails to eradicate hunger and contributes to soil degradation. Embracing sustainable farming aligns with the United Nations' sustainable development agenda, mandating the integration of innovative technologies under Agriculture 4.0. This study underscores the critical need for a paradigm shift in agricultural practices to attain sustainable farming and ensure food security for the burgeoning national population. It aims to design and construct a plant growth chamber (PGC) to collect and analyze data for implementing existing technologies into sustainable farming methods, particularly in urbanized areas. This approach optimizes environmental parameters through IoT Arduino-based smart monitoring, minimizing water and soil use and eliminating chemical inputs. This study aims to demonstrate the potential of indoor farming in the Philippines and how it can improve food production with better control and efficiency. By utilizing indoor farming methods, a more sustainable and reliable food supply can be created, addressing the challenges posed by traditional agricultural practices. It compares pak choi's growth (*Brassica Rapa* Sbsp. *Chinensis*) in a PGC-integrated hydroponic system versus conventional farming. The germination rate of the pak choi in the system was higher compared to that of grown in soil. The study found that the average calculated relative growth rate tends to be slightly higher for hydroponically grown pak choi (RGR=0.18) than for conventional pak choi (RGR=0.16). The study also observed that pak choi in the PGC has consistent relative humidity and temperature compared to conventional ones.

1. Introduction

A new paradigm of change in fundamental concepts in agriculture development is urgently needed, without such change, the goal of attaining an intensified sustainable agriculture and food security for supporting the growing global population, as per Rockström et al. (2016), which is projected to grow by 8.6 billion by 2030, and by 2050 it will be 9.8 billion will not be possible, let alone the eradication of hunger, and malnutrition (UN, 2015). The world's cropland is becoming unusable. According to specific metrics, 2.5 % of all farmlands is highly deteriorated, whereas 44 % is moderately or mildly degraded. Water resources are highly stressed, and over 40 % of the world's rural population lives in water-scarce areas. According to the BSWM (2018), the Philippines has a considerably vast quantity of arable land, most of it is unsuited for annual crop agriculture because of steep land and soil quality problems. Micronutrient deficiencies were also observed in intensively cropped Asian soils. In the Philippines, soil nutrient imbalance and decreasing nitrogen productivity have been implicated in the slowdown of crop yield growth (Kastner and Nonhebel, 2009).

Paper Received: 16 February 2024; Revised: 6 May 2024; Accepted: 22 June 2024
Please cite this article as: Ayupan C.J., Fernandes C.C., Balfermoso V.H., Atienza A.H.S., 2024, Smart Hydroponic Plant Growth Chamber with Integrated Air Conditioning System, Artificial Photosynthetic Lighting System, and Smart Monitoring System, Chemical Engineering Transactions, 112, 283-288 DOI:10.3303/CET24112048

Agriculture allowed the production of surplus food rather than scavenging and hunting. It allowed humans to focus on other activities without the worry of food scarcity and the thought of starvation. Agriculture is the foundation of the progress and development of civilization as it fueled the growth of the economy, giving significant value to countries with substantial quantities and farmable land, which allowed it to feed and grow its population. It also allows the government to sell its surplus food to other countries, enabling trading on a national scale for different forms of resources and materials (NGS, 2011). As agriculture develops, so will nations and vice versa; the domestication of crops or the adaptation of wild crops increases the plant's suitability to human requirements such as taste, yield plants, storage, and cultivation (Chen et al., 2015).

Conventional farming still makes up a majority of the agricultural sector of the Philippines. Natural calamities, shrinking farmlands, and soil degradation persist (BSWM, 2018). The need for more modern technology adoption, insufficient investment, and stagnant development in the agricultural sector hinder its progress (Purugganan, 2021). The Philippines' farming industry needs help adapting to the new paradigm shift in agriculture, which is essential for attaining sustainable intensification (Karimi et al., 2020). The move to adjust to new technologies and integrate them into the agricultural sector, such as environmentally automated controlled farms, which have been proven to double productivity and require less labor than conventional farming while yielding twice the output, will enable the country to utilize technology and resources for its development (Steensland and Zeigler, 2020). Due to the growing population and rising demand for food, there is a need to push for alternative, sustainable, and innovative farming methods. The limited availability of suitable soil for farming has made it apparent that there needs to be more than existing methods to eradicate food scarcity and ensure food security. The lack of sufficient food security threatens the population's health and affects many parts of society due to food scarcity.

This study aims to design and develop a hydroponic PGC to meet all the ventilation, lighting, and temperature requirements and the stable pH and nutrients necessary to address these problems. System parameters such as ambient temperature, relative humidity, pH, and water level will be monitored and analyzed using an Arduino-based monitoring system. The plant subject representative's parameters, such as plant length, leaf height, fresh weight, and dry weight, will be calculated and analyzed to determine the study's efficiency and capability.

2. Materials and Method

The study has built upon current innovations to test the feasibility and capability of a hydroponic PGC integrated with an air conditioning system, artificial lighting system, and a smart monitoring system. The researchers also wanted to design it with cost-efficient materials to make it noteworthy for future studies. Additionally, they aim to test various methods of hydroponic setup and processes suitable for indoor farming in an urban environment.

2.1 Site Selection

Due to the urban setting of Davao City and the limited availability of traditional farms within the city, the home of a relative of one of the researchers was chosen as the study site. This location was deemed suitable following deliberations with the research adviser, ensuring practical feasibility and relevance to urban farming conditions (CPDO, 2020).

2.2 Pak choi *(Brassica Rapa* Sbsp. *Chinensis*) Cultivation

Hydroponics system could take 30 to 45 days before harvesting, with the sowing to sprouting period alone taking 4 to 7 days. The following items listed below are the materials used by the researchers in the production of pak choi

The pak choi seeds are directly supplied by an agricultural supplier that mainly sells seeds from Ramgo International in most of the Marilog, Paquibato, and Baguio districts. Each pack contains 7 to 10 g of pak choi seed, approximately 1,500 – 2,000 seeds, and costs around 150 pesos, including shipping. The best variety of pak choi was used to test the proposed PGC. The fertilizer is also supplied by an agricultural farm, the main component of which is cow manure. In addition, the fertilizer is equally mixed with loam soil with a ratio of 1:3 for cow manure to loam soil. The resulting mixture is used to produce pak choi seedlings from transplant to the harvesting stage.

2.3 PGC and Nutrient Film Technique (NFT) Design

Using the cooling load calculations for the final design of the PGC, as seen in Figure 1, the researchers determined the size of the equipment used for the cooling system and the enclosure. The framework of the chamber enclosure is made of aluminum casing and lined with polyethylene insulation foam padding (Atienza et al., 2021). The viewing glass panel of the enclosure door is made of soda lime glass. The vapor compression refrigeration cycle is the working principle for the chamber's cooling system. An NFT hydroponic system setup was integrated into the design of the PGC to compensate for a plant's daily water needs and to maintain soil moisture. In the design of this study, the NFT is one of the many iterations of a Hydroponic setup (Niu and Masabni, 2018).

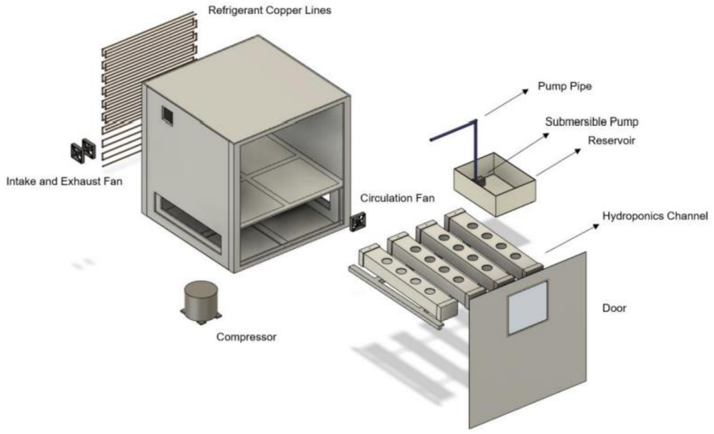

Figure 1: Exploded view of the NFT hydroponic PGC design

2.4 Adjustable Light Wavelength Intensity

The adjustable light wavelength system utilized a balanced whole spectrum Light Emitting Diodes (LEDs), which essentially uses a balanced combination of red and blue lights or purple light as well as bright white to be used in the PGC.

2.5 Smart Monitoring System

The smart monitoring system utilizes a microprocessor (NodeMCU ESP8266) to process the commands and tasks that are programmed in it to use the connected sensors such as DHT22 temperature and relative humidity sensor both inside and outside the PGC, an HC-SR04 hypersonic sensor to measure the water level of the reservoir, pH electrode to monitor the pH levels of the nutrient treated water inside the reservoir, and a BH1750 light intensity sensor to measure the light intensity of the light emitted inside the PGC, which is the fed to a user interface (UI) that can be accessed and monitored by the researchers at any time and anywhere.

2.6 Relative Growth Rate (RGR)

The analysis of plant growth is the main key point used as an analytical tool for characterizing the plant's growth. Using the formula by Suarez Rivero et al. (2016), also called the classical approach, aided the researchers in determining the relative growth rate of plants between two time intervals. Relative Growth Rate (RGR) is a relatively well-known indicator of plant strategy concerning crop yield, as identified by environmental stress and other disturbance factors, as seen in Eq(1).

$$RGR = \frac{lnW_2 - lnW_1}{t_2 - t_1} \quad (1)$$

3. Results and Discussion

The PGC indicates that it is capable of working and maintaining a temperature range of 24 to 27 °C and a relative humidity range of 75 to 80 %, all within the required optimal conditions of the pak choi plant subject, with the addition added heat load from a 100 % intensity reading from the lighting system on a 10 h operation time, and a 14 h no operation cycle. The experiment assessed 16 pak choi each for the conventional and NFT hydroponic PGC. The analysis of the temperature logs revealed significant differences between the indoor temperature of the PGC and the fluctuating outdoor temperature patterns. Despite occasional spikes and drops in outdoor temperatures, the PGC successfully maintained optimal conditions, as observed in a study on pak choi growth under elevated temperatures (Hwang et al., 2018). This study found that pak choi grown in controlled conditions exhibited consistent growth in terms of dry weight, fresh weight, and plant canopy size, unlike pak choi grown in fluctuating outdoor temperatures. Normality tests on the temperature data showed that indoor and outdoor temperatures followed a normal distribution, indicated by p-values of 0.629 and 0.06, respectively. The independent samples t-test revealed a highly significant difference (t-value of 20.53) between the two temperature environments, with a critical t-value of 1.99 at $\alpha < 0.05$. This considerable temperature contrast emphasizes the effectiveness of the PGC in maintaining stable growth conditions compared to the variable outdoor environment. Similar to the study of Hwang et al. (2018), the indoor and outdoor temperature correlates with the relative humidity, which can also affect plant growth in correlation to what type of illumination for photosynthesis was used, particularly with the plant subjects' hydration and its leaf net photosynthetic efficiency which is affected by lower humidity during high temperatures (Han et al., 2019). Results show the same effects where plant growth is significantly affected by the percentage of water in the air. The pak choi showed a significant growth rate in relative humidity higher than 80 % compared to those lower than 50 %, where it fluctuated almost every other day.

In contrast, the PGC maintained its relative humidity in an acceptable optimal range in lower temperatures, which would not alter the plant's growth (Tashiro and Wardlaw, 1991). The normality tests for indoor and outdoor humidity yielded low p-values of 0.001 and 0.02, respectively, indicating a departure from normal distribution. Consequently, the null hypothesis of normality was rejected. The Independent-Sample Mann-Whitney U test revealed a significant z-score of 7.312 (p-value = 0.001), signifying a significant difference between the indoor and outdoor humidity levels at $\alpha < 0.05$. These results highlight a substantial humidity variance between the PGC and the outdoor environment.

The effectiveness of the LED lighting system was observed in promoting pak choi growth through a blend of bright white and red lights with a ratio of 1:2 for red to white and 200 μmol/s. m² for 12-16 h daily, as Fraile-Robayo et al. (2017) supported. The research by Setiawati et al.(2022) and Fraile-Robayo et al. (2017) suggests that while bright white light aids growth, the combination of white and red LEDs shows superior growth induction compared to white light alone, albeit slightly less effective than blue and red ratio LED grow lights. A gradual decline in reservoir water levels is observed, with a notable drop during the 3rd week due to a leak promptly addressed during maintenance. This decreasing trend correlates with plant maturity, reflecting increased nutrient intake as the plants grow (Kumar and Saini, 2020).

The pH level readings throughout the growth period highlight the optimal range of 5.5 to 7.0 for nutrient availability, according to Kumar and Saini (2020). The pH levels also indicate nutrient solution status, influencing plant weight without significantly impacting chlorophyll index or dry weight accumulation (Kudirka et al., 2023). These findings contribute to understanding nutrient management for optimal plant growth and yield in hydroponic systems. Figure 2 confirmed that the effectiveness of the IoT Arduino smart monitoring system is accurate in measuring the environmental parameters within the hydroponics PGC settings. Through careful comparison with a reference measuring device, the study found that the percent error values consistently remained below 5 % which is a sound measurement system, indicating reliable performance from the smart monitoring system.

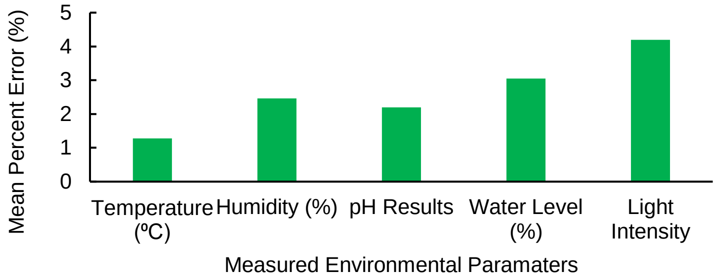

Figure 2: Percent Error Bar Graph

Observation revealed that the germination rate for pak choi cultivated in the NFT hydroponic system stands at 81 %, surpassing the conventional method, which yields 77 %. The study revealed 16 h light exposure of pak choi in PGC, while weather variation dictates the exposure time for conventional ones. It is evident that the pak choi in PGC is consistently hydrated and maintains a relative humidity of 80 %, whereas the traditional pak choi varies from 40 to 60 % due to weather fluctuations. The relative growth rates have been noted that the average of the calculated relative growth rate tends to be slightly higher towards the hydroponically PGC-grown pak choi (RGR=0.18), which is expected compared to conventional pak choi (RGR=0.16). Furthermore, by conducting a t-test, the study observed that the differences in the relative growth rates between the two groups are statistically significant, which in turn will suggest that the growth rates of the plant grown in the hydroponic system, as seen in Figure 3, are different from those grown in soil.

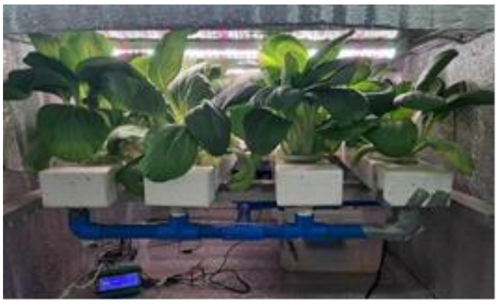

Figure 3: Grown pak choi in PGC

The PGC has shown that it is capable of maintaining a temperature range of 24 to 27 °C and was able to induce plant growth at a cycled 10–14 h photoperiod and through an NFT hydroponics as recommended by Tale et al. (2015) which is intended to test and gather data on the viability of mass producing the representative plant in a mass scale much like a plant factory with artificial lighting (PFALs) but in an urban setting that is significantly different in terms of requirements that the representative plant requires to grow to be commercially viable. Results suggest the feasibility of cultivating non-native crops in urban settings with varying temperature requirements while minimizing environmental impact and enhancing agricultural output. In the gathering of data through the user interface, an experiment was conducted in which the researcher was able to calculate its percent mean, which turned out to be a small value, meaning that the environmental parameters measured were close to its actual or real value, hence proving the implementation of an integrated IoT Arduino based monitoring system was a success.

4. Conclusion

The IoT Arduino monitoring system was beneficial for gathering and monitoring data in a PGC trial. It showed differences between hydroponically grown plants in the chamber and traditional outdoor plants. The study suggests that using innovative technologies in agriculture, especially in newer sectors, could help expand agricultural production. The experiment also showed that the integrated IoT Arduino monitoring system successfully obtained accurate environmental data. The controlled parameters in the growth chamber, such as temperature, humidity, and lighting, led to higher plant biomass than traditional soil-grown plants. However, further studies are needed to establish this method's effectiveness fully.

Nomenclature

IoT – Internet of Things
LEDs- Light Emitting Diodes
NFT - nutrient film technique
PFALs - plant factory with artificial lighting
PGC – plant growth chamber
RGR – relative growth rate, 1/day
UI – user interface
α– significance level, -

Acknowledgments

The researchers sincerely thank Mapua Malayan Colleges Mindanao, specifically the College of Engineering and Architecture, for their invaluable support and assistance during the research. The corresponding author also wants to thank Mapua Malayan Colleges Laguna and Mapua Institute of Technology at Laguna for their guidance and help.

References

Atienza A.H., Cervantes R.T., Dionisio J.A., Tan T.A., 2021, Plant growth chamber with integrated air conditioning system, periodic irrigation, and adjustable photosynthetic light wavelength, IOP Conference Series, Materials Science and Engineering, 1109(1), 12066–12066.

BSWM, 2018, Implementation of Sustainable Land Management (SLM) Practices to Address Land Degradation and Mitigate Effects of Drought, Bureau of Soil and Water Management

<bswm.da.gov.ph/program/implementation-of-sustainable-land-management-slm-practices-to-address-land-degradation-and-mitigate-effects-of-drought/> accessed 05.02.2024.

Chen Y.H., Gols R., Benrey B., 2015, Crop Domestication and Its Impact on Naturally Selected Trophic Interactions, Annual Review of Entomology, 60(1), 35–58.

CPDO, 2020, Socio Economic Indicators, Office of the City Planning and Development Coordinator of Davao City <cpdo.davaocity.gov.ph/wp-content/uploads/2021/03/SEI-2020.pdf> accessed 06.02.2024.

Fraile-Robayo R.D., Álvarez-Herrera J.G., Reyes M.A.J., Álvarez-Herrera O.F., Fraile-Robayo A.L., 2017, Evaluation of the growth and quality of lettuce (Lactuca sativa L.) in a closed recirculating hydroponic system, Agronomía Colombiana, 35(2), 216–222.

Han W., Yang Z.J., Huang L., Sun C., Yu X., Zhao M., 2019, Fuzzy comprehensive evaluation of the effects of relative air humidity on the morpho-physiological traits of Pakchoi (Brassica chinensis L.) under high temperature, Scientia Horticulturae, 246, 971–978.

Hwang S.G., Chao H.C., Lin H.L., 2018, Differential Responses of Pak Choi and Edible Amaranth to an Elevated Temperature, HortScience, 53(2), 195–199.

Karimi V., Karami E., Karami S., Keshavarz M., 2020, Adaptation to climate change through agricultural paradigm shift, Environment, Development and Sustainability, 23, 5465–5485.

Kastner T., Nonhebel S., 2010, Changes in land requirements for food in the Philippines: A historical analysis, Land Use Policy, 27(3), 853–863.

Kudirka G., Viršilė A., Sutulienė R., Laužikė K., Samuolienė G., 2023, Precise Management of Hydroponic Nutrient Solution pH: The Effects of Minor pH Changes and MES Buffer Molarity on Lettuce Physiological Properties, Horticulturae, 9(7), 837.

Kumar P., Saini S., 2020, Nutrients for Hydroponic Systems in Fruit Crops, Urban Horticulture - Necessity of the Future, In IntechOpen eBooks.

NGS, 2011, The Art and Science of Agriculture, National Geographic Society <https://education.nationalgeographic.org/resource/the-art-and-science-of-agriculture/7th-grade/?fbclid=IwAR3EeCHXXkW3usOrMkuSgOHRp_vquRu1HDmrFVnkNTl4eUrPYaWB0_N3YxI> accessed 05.02.2024.

Niu G., Masabni J., 2018, Plant Production in Controlled Environments, Horticulturae, 4(4), 28.

Purugganan J., 2021, Philippine Agriculture is Dying—What Will It Take to Save it?, Focus on the Global South <focusweb.org/philippine-agriculture-is-dying-what-will-it-take-to-save-it/> accessed 05.02.2024.

Rockström J., Williams J., Daily G., Noble A., Matthews N., Gordon L., Wetterstrand H., DeClerck F., Shah M., Steduto P., de Fraiture C., Hatibu N., Unver O., Bird J., Sibanda L., Smith J., 2016, Sustainable intensification of agriculture for human prosperity and global sustainability, Ambio, 46(1), 4–17.

Setiawati D.A., Sutiarso L., Ngadisih N., Murtiningrum M., Nugroho A.P., Putra G., Chaer M.S.I., 2022, Mathematic Modelling of Bok Choy Plant Canopy Area on Different Artificial Light at Plant Factory, Proceedings of the International Conference on Sustainable Environment, Agriculture and Tourism, Advances in Biological Sciences Research, 3-11.

Steensland A., Zeigler M., 2020, Productivity in Agriculture for a Sustainable Future, The Innovation Revolution in Agriculture, 33–69.

Suarez Rivero D., Ortiz Aguilar J., Marin Mahecha O., Velásquez Perilla P., Acevedo P., Santis Navarro A., 2016, The Effect of Magnetic and Electromagnetic Fields on the Morpho-Anatomical Characteristics of Corn (Zea mays L.) during Biomass Production, Chemical Engineering Transactions, 50, 415-420.

Tagle S., Benoza, S., Pena R., Oblea A., 2018, Development of an Indoor Hydroponic Tower for Urban Farming <dlsu.edu.ph/wp-content/uploads/pdf/conferences/ditech/proceedings/volume-3/paper-10.pdf> accessed 06.02.2024.

Tashiro T., Wardlaw I.F., 1991, The Effect of High Temperature on Kernel Dimensions and the Type and Occurrence of Kernel Damage in Rice, Australian Journal of Agricultural Research, 42, 485-496.

UN, 2015, The World Population Prospects: 2015 Revision, Department of Economic and Social Affairs, United Nations <https://www.un.org/en/development/desa/publications/world-population-prospects-2015-revision.html> accessed 06.02.2024.