



Design, Fabrication and Efficacy Testing of the Automated Hybrid-Solar Powered Hydroponic System

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ABSTRACT

The increasing demand for sustainable and climate-resilient food production systems necessitates the development of efficient soilless cultivation technologies. This study focused on the design, fabrication, and efficacy testing of an automated hybrid solar-powered hydroponic system intended for leafy vegetable production. The system was developed to address limitations of conventional hydroponics, particularly high energy consumption and dependence on unstable power supply, by integrating solar energy with grid or backup electrical support and automated environmental controls. The system was evaluated using lettuce (*Lactuca sativa*) and pechay (*Brassica rapa subsp. chinensis*) under controlled hydroponic conditions. Key parameters monitored included nutrient solution electrical conductivity (EC), temperature, humidity, and lighting conditions, with automated regulation of cooling fans, exhaust systems, and misting based on preset thresholds. Growth performance was assessed in terms of plant height, leaf development, and overall yield. Results indicated that the automated hybrid system maintained stable environmental conditions suitable for optimal plant growth, with improved consistency in nutrient delivery and microclimate control. Plants grown under the system exhibited satisfactory growth performance and uniformity, demonstrating the effectiveness of integrating solar energy and automation in hydroponic production. The system also reduced reliance on conventional electricity, contributing to lower operational costs and improved sustainability. In conclusion, the developed hybrid solar-powered hydroponic system provides a viable and energy-efficient alternative for leafy vegetable production in resource-limited and off-grid agricultural settings. The technology offers potential for wider adoption in similar climatic regions to enhance local food security and promote sustainable agriculture.

Key words: Hydroponic system, Hybrid solar-powered system, Automated agriculture Renewable energy in agriculture, lettuce production, Pechay production, climate-resilient farming, Solar-powered hydroponics

INTRODUCTION

Agriculture plays a significant role in ensuring food security, sustaining livelihoods, and supporting economic development worldwide. However, global agricultural production is increasingly threatened by climate change, environmental degradation, declining soil fertility, water scarcity, and rising energy costs. Conventional soil-based farming systems are becoming less reliable due to increasing temperatures, irregular rainfall patterns, and the growing incidence of pests and diseases, which negatively affect crop productivity and quality. These challenges have intensified the demand for sustainable and climate-resilient agricultural technologies capable of producing crops efficiently while minimizing environmental limitations. As a result,



hydroponic farming integrated with renewable energy technologies has gained global attention as an alternative production system that promotes efficient resource utilization, controlled crop production, and sustainable agricultural practices [2,5,9,11]. Hydroponic systems allow crops to grow without soil through the use of nutrient-rich water solutions under controlled environmental conditions [1,7,9]. This method reduces dependence on soil quality, minimizes soil-borne diseases, improves water and nutrient-use efficiency, and enables year-round crop production [2,6,8]. In recent years, the integration of solar energy into hydroponic systems has also become increasingly important due to rising electricity costs and the need for renewable energy sources in agriculture. Solar-powered hydroponic systems provide sustainable energy for pumps, aeration, and automation, making them particularly suitable for rural and remote farming communities [5,11]. Globally, leafy vegetables such as lettuce (*Lactuca sativa*) and pechay (*Brassica rapa*) are considered suitable crops for hydroponic cultivation because of their short growing period, high market demand, and adaptability to controlled-environment agriculture [1,3,9,10]. In the Philippines, agriculture remains one of the primary sectors contributing to food production and rural livelihoods. However, the country's agricultural industry is highly vulnerable to climatic variability, typhoons, excessive rainfall, prolonged drought, and increasing production costs.

The production of leafy vegetables such as lettuce and pechay is often affected by unfavorable environmental conditions, resulting in unstable supply and fluctuating market prices. Lettuce, in particular, is considered a high-value crop with increasing consumer demand, yet its production is limited in many lowland and warmer areas due to its sensitivity to heat stress [10,14]. Pechay, although widely cultivated and consumed, is still vulnerable to seasonal changes, pests, and diseases that reduce crop quality and productivity. These conditions highlight the need for modern and sustainable production technologies that can support continuous vegetable production while improving efficiency and reducing dependence on conventional farming systems [2,9,11]. Within the Cordillera Administrative Region (CAR) and nearby provinces, vegetable farming serves as an important agricultural activity and source of income for many communities. However, regional vegetable production is frequently challenged by fluctuating temperatures, excessive rainfall, high humidity, and climate-related disturbances that negatively affect crop growth and yield stability. Traditional soil-based cultivation in the region also faces problems related to declining soil fertility, limited arable land, and increasing vulnerability to environmental stress. The adoption of hydroponic systems integrated with renewable energy technologies may provide an alternative production strategy capable of improving crop productivity, minimizing environmental constraints, and promoting sustainable farming practices in upland and rural communities [2,5,6,9]. Despite the potential advantages of these technologies, their adoption in many areas within the region remains limited due to high operational costs, lack of technical knowledge, and limited access to modern agricultural innovations. In Luna, Apayao, agriculture remains a major source of livelihood among local residents. Leafy vegetables such as pechay are commonly cultivated and widely available in local markets, while lettuce production remains limited and is often dependent on supply from distant provinces.

Although pechay generally has high production volume, its cultivation is still greatly affected by climatic conditions. During the summer season, high temperatures and water stress contribute to poor growth, bolting, and reduced leaf quality, while excessive rainfall and high humidity during the rainy season increase pest and disease incidence, resulting in lower productivity and crop losses. Similarly, lettuce is highly sensitive to heat and moisture stress, making year-round production under conventional farming systems difficult and unreliable



[10,14,17]. These challenges affect the availability, quality, freshness, and market price of leafy vegetables in the municipality. Furthermore, traditional farming practices in Luna, Apayao are constrained by declining soil fertility, limited production areas, and vulnerability to climate variability, making continuous crop production difficult for local farmers. Despite the increasing demand for lettuce and the widespread consumption of pechay, the adoption of hydroponic technology and renewable-energy-driven agricultural systems in the locality remains limited. Therefore, there is a need to explore innovative and sustainable farming technologies that can support efficient and year-round vegetable production under local environmental conditions. Hence, this study aims to design, fabricate, and conduct efficacy testing of an automated hybrid solar-powered hydroponic system utilizing nutrient solutions within a modified shelter house for the production of lettuce and pechay in Luna, Apayao. Specifically, the study seeks to evaluate the feasibility, efficiency, and potential of the system as an alternative approach for sustainable vegetable production, improved resource utilization, and enhanced agricultural productivity in the locality [5,9,11,12].

Generally, the study aimed to design, fabricate, and evaluate the efficacy of an automated hybrid solar-powered hydroponic system for sustainable, year-round production of lettuce and pechay in Luna, Apayao. Specifically, it aims to design and fabricate an automated hybrid solar-powered hydroponic system installed in a modified greenhouse suitable for local conditions in Luna, Apayao, evaluate the performance and efficiency of the developed system in terms of energy utilization, system operation, and environmental suitability for lettuce and pechay production, and assess the growth performance and production potential of lettuce and pechay grown using the automated hybrid solar-powered hydroponic system.

METHODOLOGY

The materials used in the study were UV treated plastic sheet, insect net, G.I. pipes, 1x2 galvanize tubular, 3 inches PVC pipe, 3 inches PVS elbow, hydroponic cups, rockwool, plastic drum, hollow blocks, cement, C channel lock, reinforced steel bar, solar panel, charge controller, inverter, distribution board, DC & AC circuit breaker, 12 volts battery, automatic transfer switch, watt meter, electrical wires, temperature sensor switch, timer switch submersible pumps, aerator, exhaust fan, water soluble fertilizer, PH down formula, TDS meter, coated lettuce seeds, pechay seeds, caliper, tape measure, measuring cup.

The study was conducted from February 22 to March 22, 2026, in Barangay Lappa, Luna. The area is predominantly agricultural, where vegetable production serves as an important source of livelihood among residents. The locale experiences a tropical climate with distinct dry and rainy seasons, making protected cultivation methods such as greenhouse and hydroponic systems suitable for sustainable vegetable production. The study site was selected due to its accessibility and suitability for evaluating the automated hybrid solar-powered hydroponic system for lettuce and pechay production under local environmental conditions.

The greenhouse is 4x6 meters with total height of 3.5 meters. Post is made up of 1.5 inches G.I. pipes. A 0.20 meter wall from the natural ground level is made out of concrete and the rest is insect net supported with 1x2 galvanized tubular. Roofing is made out of UV treated plastic sheet reinforced with 1x2 galvanized tubular. Two exhaust fan is installed in the upper part of the



greenhouse to exhaust the accumulated heat from the greenhouse. The research emphasized system functionality, energy efficiency, and crop growth performance rather than treatment comparison. Lettuce (*Lactuca sativa*) and pechay (*Brassica rapa*) were used as test crops to evaluate the system's capability to support sustainable production under the climatic conditions of Luna, Apayao.

The hydroponic setup is made of 3 inches diameter PVC pipe as growing channels with four set-up elevated diagonally for proper light distribution, Hydroponics net pots were use, A 50 liters plastic drum serves as nutrient reservoir, A hose was utilized as distribution pipelines from the nutrient reservoir to the growing cahnnels. Plants were grown using a combination of recirculating nutrient film technique (NFT) or similar system where nutrient solution flowed continuously or intermittently over plant roots and kratky method, which is passive, non-circulating system where plants grow in a static nutrient solution, and roots receive oxygen from the air as the water level gradually drops. Combining these two techniques will provide continuous oxygen and nutrient supply like NFT while maintaining a water buffer for root safety in like Deep-Water Culture (DWC), making it more stable in hot climate. It also allows higher plant density and more uniform growth than Kratky, making it suitable for commercial lettuce production in Apayao. A submersible water pump was used to deliver the nutrient solution from the reservoir to the growing channels, after which the solution returned to the reservoir for reuse. This circulation ensured efficient nutrient delivery and reduced water consumption.

The solar power system served as the primary energy source for operating the hydroponic and automation components.

Solar Panels – A one unit 550 watts solar panel was installed on house roofing beside the greenhouse, It is fully exposed to the sunlight from 8 AM to 2:30 PM. These panel converted solar energy into direct current (DC) electricity, which supplied power to the system.

Charge Controller - A 45 amperes solar charge controller was connected to solar panel following the supplier manual to regulate the flow of electricity to the battery bank. Its primary function was to prevent battery overcharging during peak sunlight hours and over-discharging during low solar availability, thereby extending battery lifespan and ensuring stable system operation.

Battery Storage System – A 2 units 100AH Deep-cycle batteries was connected to the charger controller following the positive and negative charges connection. These batteries were used to store excess electrical energy generated during daytime. Stored energy allowed the system to operate continuously during cloudy conditions, nighttime, or periods of low solar radiation. The battery bank ensured uninterrupted operation of pumps, aerators, sensors, and control devices.

Hybrid Power Configuration – An automatic transfer switch (ATS) was connected to the Output of the inverter and also connected to the CAGELCO following the ATS manual. This hybrid setup was incorporated to allow automatic switching to grid power or backup supply when solar energy and battery capacity were insufficient. This ensured continuous system operation and prevented crop stress due to power interruptions.

Automation was integrated to improve system efficiency, reduce manual labor, and maintain optimal growing conditions.

Timer Switch for Water Pump Operation – An timer switch (18 time-set) was connected between the power source and the Submersible pump. This switch turn on the pump 10 minutes



for every one hour twenty minutes. The pump was set to operate at predetermined intervals to circulate the nutrient solution efficiently while conserving energy. Timed operation prevented excessive pump use, reduced power consumption, and minimized wear on mechanical components.

Timer Switch for Aerator Operation – A 20 watts aerator was installed and operated by timer switch use by submersible pumps. The aerator supplied dissolved oxygen to the nutrient solution, promoting healthy root development and preventing anaerobic conditions. Intermittent aeration ensured sufficient oxygen supply while reducing unnecessary energy use.

Temperature Sensor Switch and Cooling Fan - A temperature sensor switch was installed inside the shelter house to monitor temperature. It was installed between the power source and the fans to automatically power on if the temperature inside the greenhouse reaches 32 degrees Celsius and automatically switch off when the temperature reduced to 30 degrees Celsius. This automated cooling system helped prevent heat stress, bolting, and reduced leaf quality, especially during summer months.

Environmental Monitoring - Temperature and relative humidity inside the shelter house were continuously monitored to assess growing conditions and system performance under varying seasonal conditions.

A good quality seeds of lettuce and pechay were germinated using rockwool. The rockwool was pre-soaked with water to provide needed moisture for the seeds to germinate. Seedlings were grown in seed trays or cubes until 14 days after sowing (DAS). It was transplanted to the growing channel late at afternoon to prevent the seedlings from stress.

Nutrient solutions were prepared and measured through TDS following recommended concentrations for leafy vegetables, and it is measured every morning. For the first week (1 to 7 DAT), a 450- 550 PPM and PH of 5.5-6.0 was maintained. For the second week (8-14 DAT), a 550-700PPM and 5.5-6.0pH was maintained. For the third week (15-21 DAT), a 700-800 PPM and 5.5-6.5 PH was maintained. And for the fourth week (22-30 DAT), a 750-850 PPM and 5.5-6.5 PH was maintained. These were monitored and adjusted as needed to maintain optimal nutrient availability. Routine maintenance activities, such as checking pumps and sensors, and replenishing nutrient solution, were conducted throughout the cropping period.

Data collection focused on both system performance and crop growth parameters. System-related data included solar energy generation, battery voltage levels, power consumption of pumps, aerators, and fans, and overall system reliability. Crop-related data included plant height, number of leaves, visual plant health, and fresh weight at harvest for both lettuce and pechay. Environmental data such as temperature and humidity inside the shelter house were also recorded.

The efficacy of the automated hybrid solar-powered hydroponic system was evaluated based on system reliability, efficiency of solar energy utilization, effectiveness of automation components, and growth performance of lettuce and pechay. The system's ability to operate effectively during summer and rainy seasons was also assessed.



Collected data were analyzed using descriptive statistical tools such as means, ranges, and percentages. System efficiency and crop growth performance were evaluated against standard benchmarks for hydroponic lettuce and pechay production to determine overall system feasibility.

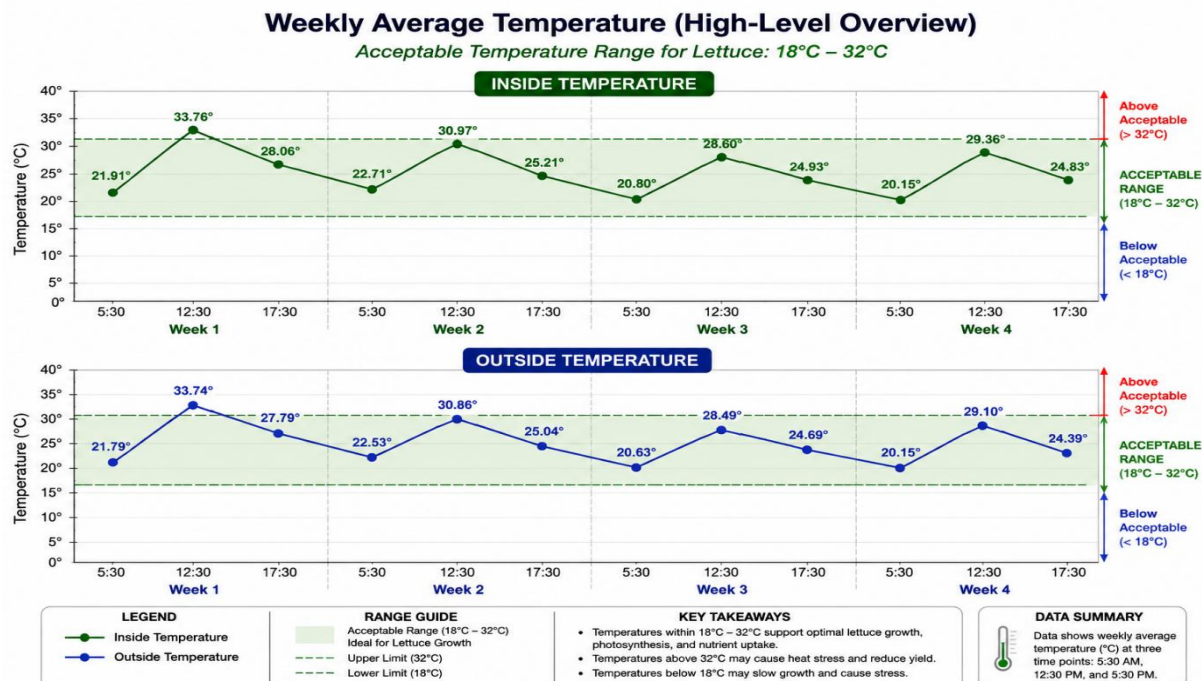
RESULTS AND DISCUSSION

The automated hybrid solar-powered hydroponic system installed inside the modified greenhouse successfully operated throughout the duration of the study. All components of the system, including the solar panel, battery storage system, automatic transfer switch, water pump, aerator, timer switches, temperature sensor switch, and cooling fans functioned according to their intended operation and preset settings. The solar-powered system provided sufficient energy to support continuous operation of the hydroponic setup, while the hybrid configuration ensured uninterrupted system performance during periods of low solar radiation and nighttime operation. The timer-controlled water pump and aerator effectively maintained nutrient circulation and oxygen supply, while the temperature-activated exhaust fans automatically regulated greenhouse temperature.

The greenhouse structure, insect netting, and yellow sticky tape traps were also effective in minimizing pest entry and infestation inside the production area. Throughout the study period, no severe insect or pest damage was observed in the lettuce and pechay plants. The insect net served as a physical barrier against flying insects, while the sticky traps helped reduce pest population inside the greenhouse. This contributed to healthier plant growth and reduced dependence on chemical pesticide application.

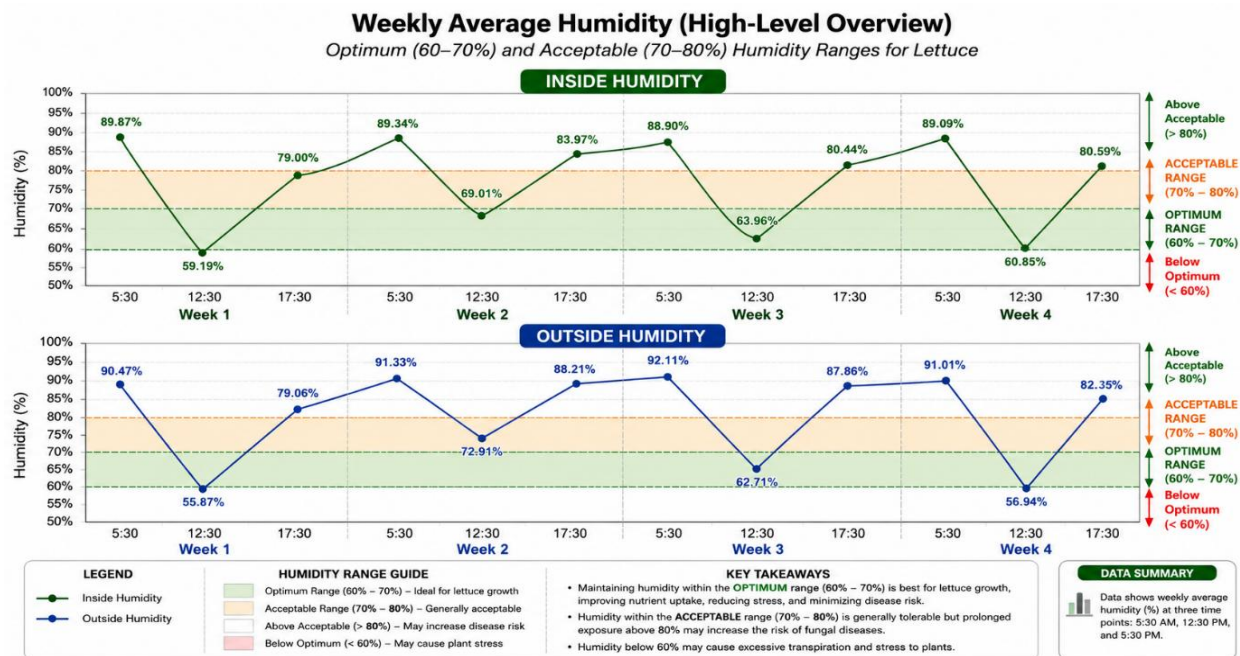
Environmental monitoring results presented in Table 3 showed that the greenhouse environment maintained relatively stable temperature and humidity conditions throughout the study period. Inside temperature during early morning ranged from 20.15°C to 22.71°C, while midday temperature ranged from 28.60°C to 33.76°C. Afternoon temperature ranged from 24.83°C to 28.06°C. The cooling and ventilation system helped regulate excessive heat accumulation inside the greenhouse, particularly during midday periods.

Figure 1: Weekly Average Temperature in selected time of the day VS Acceptable Temperature range for lettuce and pechay



Relative humidity inside the greenhouse slightly exceed acceptable levels for leafy vegetable production, with morning humidity ranging from 88.90% to 89.87%, midday humidity ranging from 59.19% to 69.01%, and afternoon humidity ranging from 79.00% to 83.97% but it more favorable compare to the outside humidity. The more stable environmental condition contributed to reduced plant stress and improved crop performance.

Figure 2: Weekly Average Humidity in selected time of the day VS acceptable humidity range for lettuce and pechay





The weekly morphological data gathered from the lettuce and pechay crops grown under the automated hydroponic system. Results showed continuous increase in plant height, number of leaves, and plant health ratings from Week 1 to Week 4 across all crops evaluated. Romaine lettuce recorded the highest plant height at Week 4 with an average of 32.25 cm, followed by Red Oak Leaf lettuce with 31.50 cm, Pechay with 27.25 cm, and Olmetie lettuce with 17.15 cm. In terms of number of leaves, both Olmetie and Red Oak Leaf lettuce recorded the highest average of 10.50 leaves, followed by Pechay with 10.00 leaves and Romaine lettuce with 8.75 leaves.

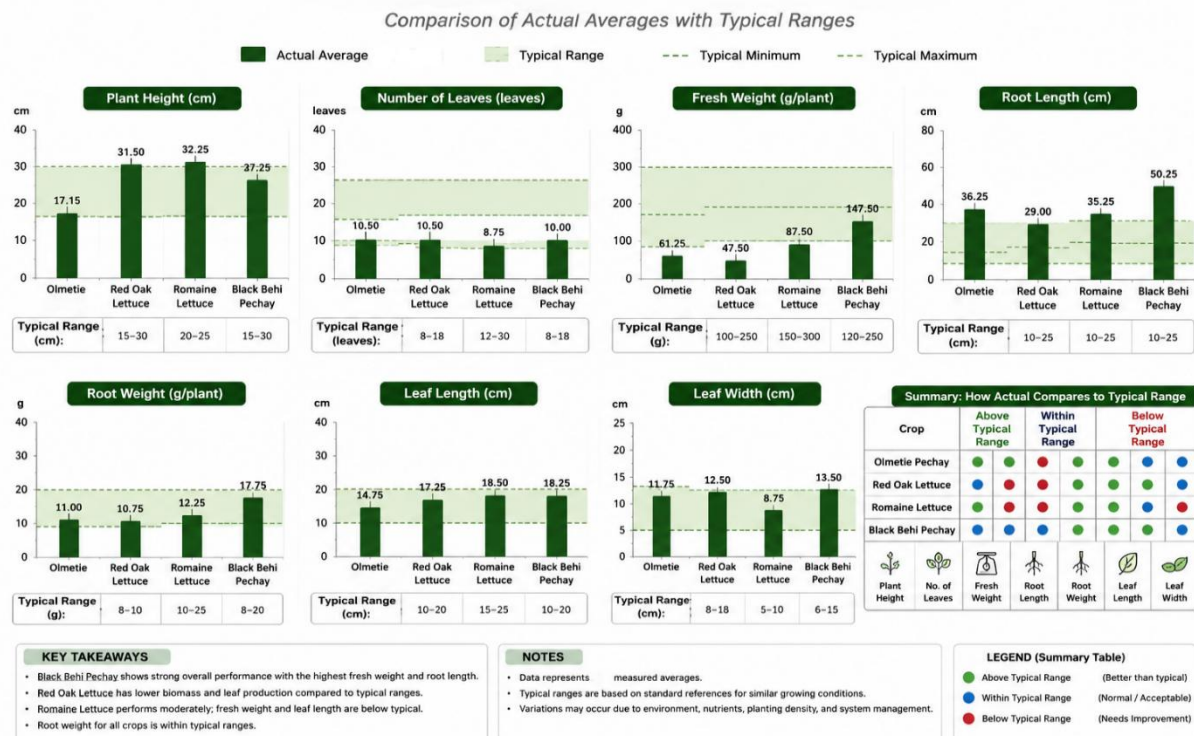
Plant health ratings also improved progressively throughout the growing period. By Week 4, Olmetie lettuce, Romaine lettuce, and Pechay obtained the highest plant health rating of 5.00, while Red Oak Leaf lettuce obtained a rating of 4.75. The consistently high plant health ratings indicated that the crops adapted well to the hydroponic environment and benefited from the stable nutrient and environmental conditions provided by the automated system.

Table 3 shows the average final morphological data gathered at harvest. Among the crops evaluated, Pechay (Black Behi) recorded the highest average fresh weight of 147.5 g, indicating superior biomass accumulation and adaptability under the prevailing environmental conditions. It also obtained the longest root length at 50.25 cm, highest root weight at 17.75 g, and widest leaf width at 13.5 cm. These results suggest that Pechay responded very well to the hydroponic growing conditions and environmental management system.

Romaine lettuce obtained the highest average plant height at 32.25 cm and produced a relatively high fresh weight of 87.5 g. It also recorded the longest average leaf length at 18.5 cm and maintained good root development with an average root length of 35.25 cm. Although Romaine lettuce exhibited satisfactory growth performance, slight reductions in fresh weight compared to pechay may have been influenced by residual heat stress associated with lowland tropical conditions.

Red Oak Leaf lettuce obtained an average fresh weight of 47.5 g with an average plant height of 31.50 cm and average leaf width of 12.5 cm. Meanwhile, Olmetie lettuce recorded an average fresh weight of 61.25 g with a plant height of 17.15 cm and root length of 36.25 cm. Despite differences in growth performance among crop varieties, all evaluated crops exhibited acceptable vegetative growth, healthy root development, and good plant vigor under the automated hydroponic system.

Figure 3 : Morphological data gathered vs the typical morphological grown in a favorable condition



The results further demonstrated the effectiveness of combining hydroponic production, renewable solar energy, greenhouse protection, and environmental automation in supporting sustainable vegetable production under local climatic conditions. The automated system minimized manual labor requirements, improved nutrient and environmental management, reduced pest infestation, and maintained continuous crop production throughout the study period. Overall, the findings confirm that the automated hybrid solar-powered hydroponic greenhouse system is technically feasible, operationally efficient, and environmentally adaptive for lettuce and pechay production in Luna. The integration of renewable energy, automation, protected cultivation, and non-chemical pest management strategies contributed to stable crop growth, improved production efficiency, and enhanced sustainability for lowland tropical vegetable production.

CONCLUSION AND RECOMMENDATION

CONCLUSION

The study successfully designed, fabricated, and evaluated an automated hybrid solar-powered hydroponic system installed inside a modified greenhouse for the production of lettuce and pechay in Lappa. The findings demonstrated that the integration of hydroponic technology, solar energy, and protected cultivation can provide an effective and sustainable alternative to conventional vegetable production under the climatic conditions of the locality.

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The hybrid solar power system was capable of supplying sufficient and reliable energy for the operation of pumps, aerators, cooling fans, and automation devices, ensuring continuous system functionality even during periods of limited solar radiation. The incorporation of automation components such as timer-controlled pumps, aerators, and temperature-activated cooling fans contributed to improved operational efficiency, reduced labor requirements, and more stable environmental conditions inside the greenhouse.

The modified greenhouse structure significantly improved the production environment by protecting crops from excessive rainfall, extreme heat, and pest intrusion. The use of insect netting and yellow sticky tape traps effectively supported integrated pest management, reducing insect infestation and minimizing dependence on chemical pesticides. The greenhouse environment also allowed continuous crop production during prolonged rainy periods, when conventional open-field vegetable production is often difficult in the locality.

Both lettuce and pechay exhibited satisfactory growth and development under the automated hydroponic system in terms of plant height, leaf length, leaf width, root weight and root length. Among the test crops, Black Behi pechay showed superior adaptability and biomass production under lowland tropical conditions, while romaine lettuce demonstrated acceptable growth performance despite minor heat-related limitations. Overall, the system proved technically feasible, environmentally adaptive, and operationally efficient for year-round leafy vegetable production in Luna, Apayao.

The study therefore confirms that an automated hybrid solar-powered hydroponic greenhouse system has strong potential as a sustainable agricultural technology for improving vegetable productivity, resource-use efficiency, climate resilience, and local food availability in lowland rural communities.

RECOMMENDATIONS

Based on the findings of the study, the following recommendations are proposed:

1. Although the design and fabrication meets the expectation and successfully completed, it is recommended to construct a minimum of 6 meters width and 12 meters length with at least 4.5 meters height and the roofing design should be monitor type to minimize sudden change temperature from outside.
2. The automated hybrid solar-powered hydroponic system may be adopted and promoted among farmers, agricultural institutions, and research stations in Luna and nearby areas as an alternative technology for sustainable vegetable production.
3. Future studies may evaluate additional leafy vegetables and high-value crops suitable for hydroponic production under lowland tropical conditions to further expand the applicability of the system.
4. Further improvement of the greenhouse cooling and ventilation system such as installation of cooling pads and automated mister is recommended to better regulate temperature during extreme summer conditions, particularly for heat-sensitive crops such as lettuce.
5. Additional research may be conducted on the use of organic or bio-based nutrient solutions, including vermi-based nutrient formulations, to enhance sustainability and reduce dependence on commercial inorganic hydroponic fertilizers.
6. The 12 volts inverter performs well during the conduct of study, however using 24 volt inverter is recommended to reduce the risk of wire overheating.



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