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Research Article

Evaluation of the Effectiveness of PWM and MPPT Controllers in Improving the Performance of Off-Grid Solar Power Plants in NFT Hydroponic Systems

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ABSTRACT

Purpose of the study: The decreasing availability of agricultural land and the growing demand for sustainable food production have encouraged the adoption of hydroponic cultivation systems supported by renewable energy sources. In off-grid Nutrient Film Technique (NFT) hydroponic systems, the reliability of electrical power—particularly for continuous pump operation—is critical for plant growth.

Methodology: A quantitative experimental approach was employed using a 50 Wp solar panel, a 12 V 10 Ah battery, and a 12 W DC water pump operating under identical system configurations. Electrical parameters, including charging voltage, current, and power, were measured during daylight hours, while nighttime pump operating duration was used as a functional performance indicator.

Main Findings: The results demonstrate that the MPPT controller consistently produced higher and more stable charging power (up to 13.05 W) compared to the PWM controller (approximately 12 W). This improved charging performance translated into longer nighttime pump operation, with MPPT sustaining operation for up to 11 hours 40 minutes, whereas PWM supported only 9 hours 30 minutes to 10 hours 15 minutes. The findings confirm that MPPT controllers are more effective in optimizing solar energy utilization and enhancing battery endurance in real-world hydroponic applications.

Novelty/Originality of this study: The novelty of this study lies in its integration of electrical performance analysis with practical operational outcomes, offering applied insights for the design of reliable and sustainable solar-powered hydroponic systems, particularly in regions with limited grid access.

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1. INTRODUCTION

Indonesia is widely recognized as an agrarian country with substantial agricultural potential that plays a strategic role in supporting national food security. With a population of approximately 272 million people, the agricultural sector remains a primary source of livelihood for a significant proportion of Indonesian households

[1]-[5]. However, despite its agrarian identity, Indonesia currently faces structural challenges in the agricultural sector, particularly the ongoing decline in productive agricultural land. National data indicate that the total area of arable land reached 7,463,948 hectares in 2019 and has continued to decline in subsequent years due to land conversion, urban expansion, and industrial development. This issue is particularly evident in Central Java, a province designated as one of the national food buffer zones, where land availability is increasingly constrained.

The shrinking availability of agricultural land necessitates the adoption of innovative and space-efficient farming technologies capable of maintaining or increasing productivity under limited land conditions. One such technology is hydroponic cultivation, a soil-less agricultural system that utilizes nutrient-enriched water as the primary growing medium [6]-[11]. Hydroponics offers several advantages, including higher water-use efficiency, controlled nutrient delivery, and suitability for urban and peri-urban environments with minimal land availability. Among various hydroponic techniques, the Nutrient Film Technique (NFT) system has gained widespread adoption due to its relatively simple structure, low water volume requirements, and suitability for leafy vegetable production [12]-[17].

In NFT hydroponic systems, plant roots are continuously exposed to a thin film of circulating nutrient solution, allowing efficient nutrient uptake while maintaining adequate oxygenation [18]-[21]. A critical component of this system is the water pump, which ensures uninterrupted nutrient circulation to plant roots. The operational reliability of the water pump directly affects plant growth, as interruptions in nutrient flow can rapidly lead to plant stress or crop failure [22]-[25]. Consequently, the availability and stability of electrical power to drive the pump are central challenges, particularly in remote areas with limited grid access or in efforts to reduce long-term operational costs and carbon emissions.

Renewable energy, particularly solar energy, presents a viable solution for powering hydroponic systems sustainably. Off-grid photovoltaic solar power plants (PLTS) utilize solar panels, batteries, and power regulation components to generate and store electrical energy independently of the utility grid [25]-[29]. The integration of off-grid PLTS with hydroponic systems enables continuous nutrient circulation while reducing dependence on fossil-fuel-based electricity sources [30]-[32]. In this configuration, the battery serves as a crucial energy storage unit, ensuring system operability during periods of low solar irradiance or at night.

However, the performance and reliability of off-grid PLTS systems are highly dependent on the Solar Charge Controller (SCC), a component that regulates the charging and discharging processes among solar panels, batteries, and electrical loads. The SCC prevents battery overcharging, excessive discharge, and voltage instability, all of which can significantly affect battery lifespan and system performance. Two SCC technologies are commonly used in small-scale photovoltaic systems: Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT). PWM controllers operate by directly matching the panel voltage to the battery voltage, while MPPT controllers dynamically track the optimal power point of the solar panel to maximize energy harvesting efficiency [33]-[35]

Although numerous studies have investigated solar-powered hydroponic systems, existing research predominantly focuses on system design, feasibility analysis, or general electrical efficiency metrics [36], [37]. Importantly, a clear research gap remains: limited experimental studies directly compare the performance of PWM and MPPT solar charge controllers under identical operational conditions in real-world hydroponic applications. Furthermore, prior studies often emphasize electrical parameters such as voltage, current, and charging efficiency, while overlooking practical performance indicators, such as battery endurance and nighttime pump operating duration, which are critical for maintaining continuous nutrient circulation in NFT systems.

Addressing this gap, the present study conducts an experimental comparison of PWM and MPPT solar charge controllers in an off-grid photovoltaic-powered NFT hydroponic system. The analysis focuses not only on electrical charging characteristics but also on real-world operational outcomes, including battery charging effectiveness and pump operating duration during periods of non-irradiance. By integrating electrical performance metrics with functional system resilience indicators, this research offers a more comprehensive evaluation of SCC effectiveness in supporting sustainable hydroponic cultivation. Ultimately, this study aims to provide practical and applicable technical recommendations for the development of efficient, resilient, and sustainable renewable energy-based hydroponic systems, particularly in regions facing land scarcity and energy access constraints. The findings are expected to contribute to both the scientific literature on photovoltaic system optimization and the practical implementation of solar-powered agriculture in developing countries.

2. RESEARCH METHOD

This study adopted a quantitative experimental methodology with a system-level engineering approach to rigorously evaluate the performance of Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT) solar charge controllers in an off-grid photovoltaic (PV) powered hydroponic application. The experimental framework was designed to isolate the influence of charge controller topology on energy harvesting efficiency, battery charging dynamics, and load endurance under real-world operating conditions. The investigation emphasizes both electrical performance metrics and functional system outcomes, thereby ensuring technical relevance for renewable energy and power electronics applications. The photovoltaic subsystem consisted of a 50 Wp polycrystalline PV module with a nominal maximum power point voltage (Vmp) of approximately 18 V and an open-circuit voltage (Voc) of 21–22 V. Energy storage was provided by a 12 V, 10 Ah sealed lead-acid battery with a nominal energy capacity of 120 Wh. A 12 V DC centrifugal water pump rated at 12 W was employed as the continuous load within a Nutrient Film Technique (NFT) hydroponic system. Two commercially available solar charge controllers, PWM and MPPT, were integrated alternately into the system. To ensure experimental control, all system components, cable lengths, conductor cross-sections, and electrical protection devices were maintained identical across both test configurations.

The PWM charge controller operates by directly modulating the duty cycle of the switching element to regulate battery charging voltage, effectively forcing the PV module voltage to follow the battery voltage during the bulk and absorption phases. In contrast, the MPPT controller incorporates a DC–DC conversion stage and a maximum power point tracking algorithm to decouple PV operating voltage from battery voltage, allowing the PV module to operate near its optimal power point regardless of battery state of charge. This fundamental architectural difference forms the primary technical basis for performance comparison in this study.

Experimental measurements focused on both charging-phase and load-phase performance. During daylight operation, voltage and current at the controller output were measured at two-hour intervals between 08.00 and 16.00 WIB using calibrated digital multimeters and clamp meters with measurement uncertainties below ±1%. Instantaneous charging power was computed as the product of measured voltage and current. A lux meter was utilized to record relative solar irradiance during each measurement period, enabling correlation between environmental conditions and electrical performance. All measurements were conducted under loaded conditions, with the DC pump operating continuously, to reflect realistic system behavior rather than no-load or laboratory-ideal scenarios. To evaluate battery utilization efficiency and system endurance, nighttime operational tests were conducted by allowing the fully charged battery to supply the DC pump continuously starting at 18.00 WIB. The pump operating duration was recorded until the battery voltage reached the minimum safe discharge threshold defined by the controller's low-voltage disconnect setting. This procedure was repeated over four consecutive days for each controller type under varying meteorological conditions, including differences in cloud cover and ambient temperature, which were recorded to assess their influence on PV output and charging performance.

Data analysis was performed using comparative and descriptive statistical techniques. Charging voltage, current, and power profiles were analyzed to identify trends in energy conversion efficiency and stability between PWM and MPPT controllers. Pump operating duration was used as an integrative performance indicator, reflecting cumulative charging efficiency, battery state-of-charge management, and load supply capability. Performance differences were interpreted in the context of PV operating point control, conversion efficiency, and thermal sensitivity of PV modules. To ensure experimental validity and reproducibility, multiple measurement cycles were conducted, and instrument calibration was verified prior to data acquisition. The experimental design controlled all variables except the type of solar charge controller, allowing observed differences in performance to be attributed directly to controller topology and control strategy. This methodological framework provides a robust basis for evaluating charge controller selection in small-scale off-grid PV systems intended for continuous-load agricultural applications.

3. RESULTS AND DISCUSSION

This research successfully designed and implemented a performance comparison system for PWM and MPPT-type Solar Charge Controllers (SCCs) on an off-grid solar power plant based on 50 Wp solar panels to charge a 12V 10Ah battery used as the power source for a 12V DC pump. This system was created to determine the difference in effectiveness between the two types of SCC in optimizing energy absorption from solar panels and in determining the duration of pump operation at night. In the test, solar panels were used as the main energy source to charge the battery. Energy from the panel was then regulated by PWM or MPPT SCC, each of which has different characteristics in handling the panel's voltage and current. PWM SCC works by pulling the panel voltage close to the battery voltage, while MPPT SCC keeps the panel at the maximum power point (Vmp ≈ 18V) so it can produce a higher charging current.

Figure 1. Wiring Diagram

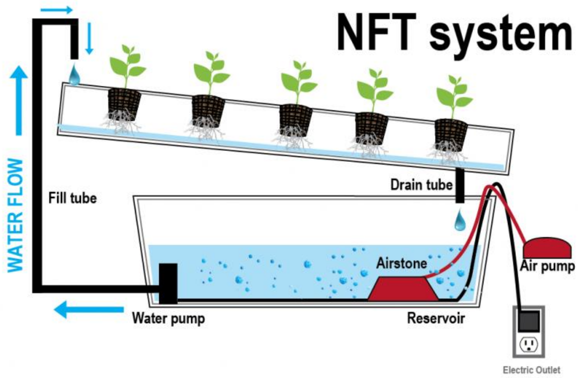

Figure 2. Hidroponik system NFT

3.1. Data Collection Results

Data collection was carried out by recording the voltage, current, and power generated by the solar panels every hour between 8:00 AM and 4:00 PM WIB. This data was collected to determine the performance differences between SCC PWM and MPPT in the charging process of a 12V 10Ah battery with the pump active. The complete measurement results are shown in Table 1 and Figure 3.

Table 1. Data acquisition with SCC PWM

Time	Voltage (V)	Current (A)	Power (W)
08.00	11.23	1.08	12.12
10.00	12.02	1.02	12.26
12.00	12.42	1.02	12.66
14.00	12.38	0.98	12.13
16.00	12.05	0.98	11.8

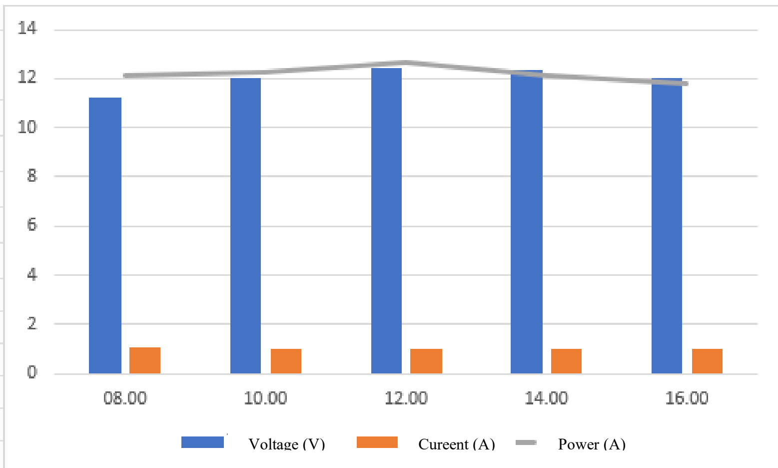

Figure 3. Data graph with SCC PWM

Table 1 and Figure 3 show the results of SCC PWM data collection over two-hour intervals from 8:00 AM to 4:00 PM. The panel voltage was recorded in the range of 11.23–12.42 V, with a current of 0.98–1.08 A, resulting in a power output of 11.8–12.66 W. The highest value occurred at 12:00 PM when sunlight intensity was at its peak, indicated by an increase in voltage and power. The graph also shows a similar pattern, with voltage and power increasing towards midday and then decreasing again in the afternoon, while the current remained relatively stable. Overall, these data indicate that the SCC PWM can maintain a power output of approximately 12 W for pumping, although power output fluctuates with changes in sunlight intensity.

Table 2. Data Collection with MPPT

Time	Voltage (V)	Current (A)	Power (W)
08.00	12.04	1.02	12.28
10.00	12.32	1	12.32
12.00	13.02	0.99	12.88
14.00	13.05	1	13.05
16.00	12.21	1.02	12.45

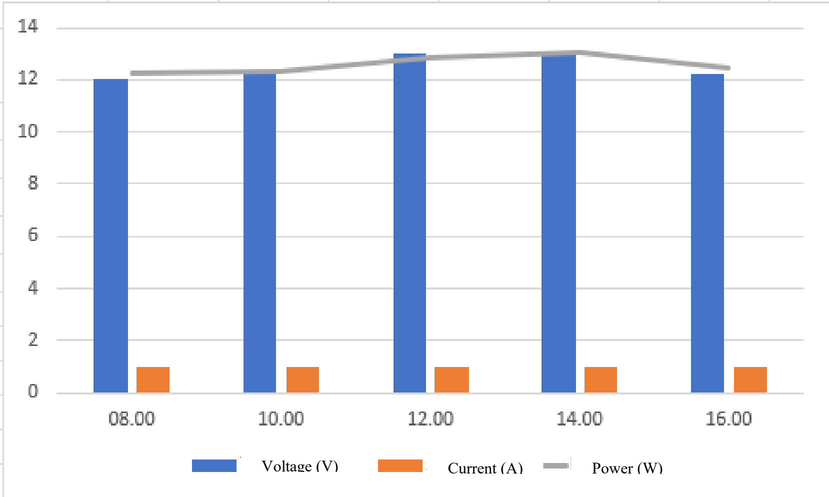

Figure 4. Data graph with MPPT

The table 2 and figure 4 show the results of SCC MPPT data collection every two hours from 8:00 AM to 4:00 PM. The panel's voltage output ranges from 12.04–13.05 V, with a current of 0.99–1.02 A, resulting in a battery power input of 12.28–13.05 W. The graph shows that the voltage and power values increase, peaking at 2:00 PM, when the power reaches 13.05 W, then decrease slightly towards 4:00 PM as sunlight intensity decreases. The current remains relatively stable throughout the measurements, demonstrating the MPPT's ability to maintain optimal power flow despite changes in irradiance. Overall, these data demonstrate that the SCC MPPT can produce a more stable power output, approach the maximum pump load, and result in a more efficient battery charging process compared to the SCC PWM system.

3.2. Effectiveness of SCC PWM & MPPT on Pumps

The following are the results of SCC PWM and MPPT recordings over four days with a 12 W pump operating at night starting at 6:00 PM; a nominal battery capacity of 120 Wh; and the difference in MPPT/PWM is evident in the charging margin.

Table 3. SCC PWM Observation Results

Day	Weather	Temperature (°C)	Pump Condition
1	Cloudy	28	Endure 9 Hours 30 Minutes
2	Sunny	30	Endure 10 Hours 15 Minutes
3	Sunny	33	Endure 10 Hours
4	Sunny	32	Endure 9 Hours 40 Minutes

Table 4. MPPT Observation Results

Day	Weather	Temperature (°C)	Pump Condition
1	Sunny	33	Endure for 11 hours
2	Sunny	32	Endure 10 Hours 45 Minutes
3	Cloudy	30	Endure 10 Hours 15 Minutes
4	Sunny	34	Endure 11 Hours 40 Minutes

These two tables compare pump run times in the SCC PWM and MPPT systems over four days of observations, with varying weather and temperature. With the SCC PWM, the pump operated for 9 hours 30 minutes to 10 hours 15 minutes, with the best performance on sunny days at 30–33°C. Meanwhile, the SCC MPPT delivered longer, more stable runtimes, ranging from 10 hours 15 minutes to 11 hours 40 minutes, with the longest run on sunny days at 34°C. Overall, the MPPT proved more efficient in optimizing battery charging, allowing the pump to operate longer than the PWM under relatively similar weather and temperature conditions.

The results show that the differences in operating characteristics between the PWM and MPPT types of Solar Charge Controllers (SCC) significantly impact the effectiveness of battery charging and the duration of pump operation in the NFT hydroponic system based on off-grid solar power plants. During the battery charging test, the SCC PWM produced a charging voltage in the range of 11.23–12.42 V with an average power of approximately 12 W. This value indicates that the PWM operates by adjusting the panel voltage closer to the battery voltage, so the energy absorbed by the panel is not fully at its maximum power point. This condition aligns with the characteristics of PWM, which essentially functions only as an electronic switch and does not optimize the maximum power point of the solar panel. Therefore, its efficiency is highly dependent on the compatibility of the panel and battery voltages [38]-[40]

In contrast, the SCC MPPT demonstrated superior performance, with a higher and more stable charging voltage in the range 12.04–13.05 V and a power output of 13.05 W under optimal light intensity. The MPPT maintains the solar panel at its maximum power point (Vmp), enabling optimal utilization of the panel's energy output despite fluctuations in irradiance and ambient temperature. This finding aligns with research by Manna et al [41] and Eltamaly et al [42], who reported that MPPT can increase the efficiency of solar energy utilization by employing a maximum power tracking algorithm that is adaptive to changes in environmental conditions. The current stability demonstrated by the MPPT during measurements also indicates the system's ability to maintain continuous battery charging. A relatively constant current despite voltage fluctuations indicates that the MPPT is actively adjusting the power conversion ratio, thus minimizing energy loss. This is particularly important in small-scale solar PV systems with limited battery capacity, as any increase in charging efficiency directly increases energy availability at night [43]-[47]

This difference in charging performance directly impacts the duration of hydroponic pump operation at night. Based on observations over four days, the SCC PWM maintained pump operation for only 9 hours 30 minutes to 10 hours 15 minutes, whereas the SCC MPPT extended the operation duration to 11 hours 40 minutes in sunny weather. This difference indicates that the MPPT can generate greater energy reserves in the battery than the PWM. These results are consistent with Orakwue et al [48], who reported that the use of MPPT in solar-powered hydroponic systems significantly increased load operating time compared to PWM control. The influence of weather and temperature conditions was also evident in the results of this study. On sunny days with relatively high temperatures, MPPT can maintain a more stable pump operating duration than PWM. This indicates that MPPT has greater tolerance to increases in panel temperature, which generally decreases the solar panel output voltage. The MPPT's ability to compensate for these conditions makes it more reliable for sustainable agricultural applications that require a continuous energy supply, such as NFT hydroponic systems that rely heavily on constant nutrient circulation [49]-[51]

The novelty of this study lies in its experimental evaluation of PWM and MPPT solar charge controllers within an operational NFT hydroponic system powered by an off-grid photovoltaic source. Unlike previous studies that focus primarily on electrical performance metrics, this research highlights the practical implications of controller selection by directly linking charging efficiency to nighttime pump operating duration, thereby providing applied insights for small-scale renewable energy-based agricultural systems. The findings of this study have important technical and practical implications for the development of renewable energy-based agricultural systems. From a technical perspective, the superior performance of MPPT controllers demonstrates their ability to maximize photovoltaic energy utilization and improve battery charging efficiency. Practically, the results provide guidance for farmers and urban growers in selecting appropriate energy management components to ensure reliable hydroponic operation, particularly in areas with limited grid access. Additionally, this study supports policy initiatives promoting sustainable agriculture through the integration of renewable energy technologies.

Despite its contributions, this study has several limitations. The experimental system was limited to a single photovoltaic capacity and battery specification, which may affect the generalizability of the results to larger or different system configurations. Furthermore, the study did not include an economic cost analysis or long-term performance assessment, and the observation period was relatively short, limiting insights into seasonal variations and component degradation. Future research should expand upon this study by evaluating different photovoltaic capacities, battery technologies, and load variations to obtain a more comprehensive understanding of system performance. Incorporating economic and lifecycle cost analyses would provide valuable insights into the financial feasibility of PWM and MPPT controllers. Additionally, long-term testing across different seasons and the integration of smart monitoring systems are recommended to enhance the reliability and scalability of solar-powered hydroponic systems.

Overall, the results of this study confirm that SCC selection is a crucial factor in designing off-grid solar power systems for hydroponic applications. MPPT has been shown to be more efficient at maximizing solar panel output, improving battery charging efficiency, and extending pump operation at night. These findings reinforce previous research results and provide additional empirical evidence at a real-system scale, thus providing the basis for technical recommendations for the development of more reliable and sustainable renewable energy-based hydroponic systems.

4. CONCLUSION

Based on the research findings, this study concludes that the selection of the Solar Charge Controller (SCC) type plays a decisive role in determining battery charging effectiveness and the continuity of nighttime pump operation in off-grid solar-powered systems. The MPPT-type SCC demonstrates consistently superior performance compared to the PWM controller, as evidenced by its ability to produce higher and more stable charging voltage and power. This technical advantage translates directly into longer pump operating durations at night, with MPPT maintaining operation for approximately 10 hours 15 minutes to 11 hours 40 minutes, whereas PWM systems operate for only about 9 hours 30 minutes to 10 hours 15 minutes. These results indicate that MPPT controllers are more effective in maximizing solar panel output and optimizing the battery charging process, particularly under variable irradiance conditions. The implications of this finding are significant for the design and implementation of small-scale solar power systems, especially in applications that demand uninterrupted nighttime operation, such as NFT hydroponic water pumps. Practically, adopting MPPT controllers can enhance system reliability, energy efficiency, and operational sustainability, thereby reducing the risk of nutrient flow disruption that could negatively affect plant growth. From a broader perspective, this study underscores the importance of appropriate component selection in renewable energy systems and supports the wider adoption of MPPT-based solutions for off-grid agricultural and hydroponic applications that rely on stable and continuous energy supply.

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AUTHOR CONTRIBUTIONS

TSW designed the study, conducted the analysis, collected the data, and wrote the manuscript. MK supported the availability of research data, and reviewed the research results.

CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

REFERENCES

[1] A. Sudomo, B. Leksono, H. L. Tata, A. A. D. Rahayu, A. Umroni, H. Rianawati, A. Asmaliyah, K. Krisnawati, A. Setyayudi, M. M. B. Utomo, L. V. A. Pieter, A. Wresta, Y. Indrajaya, S. A. Rahman, and H. Baral, "Can agroforestry contribute to food and livelihood security for Indonesia's smallholders in the climate change era?," *Agriculture*, vol. 13, no. 10, pp. 1896, 2023, doi: 10.3390/agriculture13101896.

[2] R. A. Budi Kusumo, G. Kurnia, I. Setiawan, and R. Tirtosudarmo, "Migration and farmer household livelihood strategies: Factors influencing the decision to migrate," *Pertanika Journal of Social Sciences & Humanities*, vol. 31, no. 1, 2023, doi: 10.47836/pjssh.31.1.04.

[3] A. H. Harianja, Y. Adalina, G. Pasaribu, I. Winarni, R. Maharani, A. Fernandes, ... and H. Kuspradini, "Potential of beekeeping to support the livelihood, economy, society, and environment of Indonesia," *Forests*, vol. 14, no. 2, pp. 321, 2023, doi: 10.3390/f14020321.

[4] S. Setiani, D. E. Wijayanti, and M. W. Priyanto, "Determinant of maize farmers household food security in dry land Madura Island, Indonesia," *Agrisocionomics: Jurnal Sosial Ekonomi Pertanian*, vol. 9, no. 1, pp. 41-56, 2025, doi: 10.14710/agrisocionomics.v9i1.23053.

[5] B. S. Situmorang, R. F. Putri, S. R. Giyarsih, G. T. Gunawan, and G. J. Yustindra, "The dynamics of extreme poverty: Livelihood and empowerment strategies in a West Java Village, Indonesia," *GeoJournal*, vol. 90, no. 6, pp. 1-12, 2025, doi: 10.1007/s10708-025-11536-w.

[6] A. Fussy, and J. Papenbrock, "An overview of soil and soilless cultivation techniques—chances, challenges and the neglected question of sustainability," *Plants*, vol. 11, no. 9, pp. 1153, 2022, doi: 10.3390/plants11091153.

[7] H. Kuriyal, I. Shah, S. Rana, and A. Kumar, "Chapter-15 hydroponics or soil-less farming technology in horticulture," *Modern Concepts in Farming*, vol. 199, 2022.

[8] A. Sharma, C. Manpoong, V. S. Devadas, B. D. Kartha, H. Pandey, and M. Wangsu, "Crop hydroponics, phyto-hydroponics, crop production, and factors affecting soilless culture," *ACS Agricultural Science & Technology*, vol.2, no. 6, pp. 1134-1150, 2022, doi: 10.1021/acsagscitech.2c00243.

[9] P. Renganathan, E. O. R. Puente, N. V. Sukhanova, and L. A. Gaysina, "Hydroponics with microalgae and cyanobacteria: Emerging trends and opportunities in modern agriculture," *BioTech*, vol. 13, no. 3, pp. 27, 2024, doi: 10.3390/biotech13030027.

[10] I. Szekely, and M. H. Jijakli, "Bioponics as a promising approach to sustainable agriculture: A review of the main methods for producing organic nutrient solution for hydroponics," *Water*, vol. 14, no. 23, pp. 3975, 2022, doi: 10.3390/w14233975.

[11] R. B. Malabadi, K. P. Kolkar, R. K. Chalannavar, K. V. C. Coronado, S. S. Mammadova, H. Baijnath, and G. Abdi, "Greenhouse farming: Hydroponic vertical farming-Internet of Things (IOT) Technologies: An updated review," *World Journal of Advanced Research and Reviews*, vol. 23, no. 2, pp. 2634-2686, 2024, doi: 10.30574/wjarr.2024.23.2.2595.

[12] O. D. Palmitessa, A. Signore, and P. Santamaria, "Advancements and future perspectives in nutrient film technique hydroponic system: A comprehensive review and bibliometric analysis," *Frontiers in Plant Science*, vol. 15, pp. 1504792, 2024, doi: 10.3389/fpls.2024.1504792.

[13] G. Carrasco, F. Fuentes-Peñailillo, P. Manríquez, P. Rebolledo, R. Vega, K. Gutter, and M. Urrestarazu, "Enhancing leafy greens' production: Nutrient film technique systems and automation in container-based vertical farming," *Agronomy*, vol. 14, no. 9, pp. 1932, 2024, doi: 10.3390/agronomy14091932.

[14] A. G. Bhat, M. Hasan, D. K. Singh, R. N. Sahoo, M. Yeasin, V. Paradkar, S, Mukherjee, and S. V. Kumar, "Design and development of multilayer, nutrient film hydroponic vertical farming system for green leafy vegetables," *Journal of Community Mobilization and Sustainable Development*, vol. 19, no. 4, pp. 1243-1250, 2024, doi: 10.5958/2231-6736.2024.00248.X.

[15] S. A. Gillani, R. Abbasi, P. Martinez, and R. Ahmad, "Comparison of energy-use efficiency for lettuce plantation under nutrient film technique and deep-water culture hydroponic systems," *Procedia Computer Science*, vol. 217, pp. 11-19, 2023, doi: 10.1016/j.procs.2022.12.197.

[16] S. Rajendran, T. Domalachenpa, H. Arora, P. Li, A. Sharma, and G. Rajauria, "Hydroponics: Exploring innovative sustainable technologies and applications across crop production, with Emphasis on potato mini-tuber cultivation," *Heliyon*, vol. 10, no. 5, 2024, doi: 10.1016/j.heliyon.2024.e26823.

[17] M. N. Reza, K. H. Lee, M. R. Karim, M. A. Haque, E. Bicamumakuba, P. K. Dey, Y. Y. Jang, and S. O. Chung, "Trends of soil and solution nutrient sensing for open field and hydroponic cultivation in facilitated smart agriculture," *Sensors*, vol. 25, no. 2, pp. 453, 2025, doi: 10.3390/s25020453.

[18] O. A. Nitu, E. Ş. Ivan, A. S. Tronac, and A. Arshad, "Optimizing lettuce growth in nutrient film technique hydroponics: evaluating the impact of elevated oxygen concentrations in the root zone under LED illumination," *Agronomy*, vol. 14, no. 9, pp. *14*(9), 1896, 2024, doi: 10.3390/agronomy14091896.

[19] M. Rajalakshmi, and K. Gunasekaran, "Investigations on the money plant's nutrient removal efficiency in nutrient film technique hydroponic system employing synthetic wastewater," *Environmental Quality Management*, vol. 34, no. 4, pp. 70080, 2025, doi: 10.1002/tqem.70080.

[20] J. Liu, J. Masabni, and G. Niu, "Intermittent flow alleviated root zone stress and increased organic lettuce yield in nutrient film technique," *HortScience*, vol. 60, no. 7, pp. 1208-1217, 2025, doi: 10.21273/HORTSCI18623-25.

[21] S. Dhandapani, V. S. Philip, S. A. A. N. Nasreen, and B. S. Park, "Advanced growth device boosts hydroponic efficiency: Enhancing yield and quality while reducing crop production cost and algae contamination," *Environmental Technology & Innovation*, vol. 37, pp. 104051, 2025, doi: 10.1016/j.eti.2025.104051.

[22] T. Sangeetha, and E. Periyathambi, "Automatic nutrient estimator: distributing nutrient solution in hydroponic plants based on plant growth," *PeerJ Computer Science*, vol. 10, pp. e1871, 2024, doi: 10.7717/peerj-cs.1871.

[23] B. Q. Nguyen, S. A. Kantoush, T. H. Nguyen, T. T. Bui, R. S. Nguyen, T. N. Doan, and D. N. Vo, "Cumulative impacts of interbasin water transfer and salinity intrusion on water security in central Vietnam," *Science of The Total Environment*, vol. 998, pp. 180250, 2025, doi: 10.1016/j.scitotenv.2025.180250.

[24] C. Kaya, "Intelligent environmental control in plant factories: integrating sensors, automation, and AI for optimal crop production," *Food and Energy Security*, vol. 14, no. 1, pp. e70026, 2025, doi: 10.1002/fes3.70026.

[25] M. E. Abalasei, D. Toma, M. Dorus, and C. Teodosiu, "The impact of climate change on water quality: A critical analysis," *Water*, vol. 17, no. 21, pp. 3108, 2025, doi: 10.3390/w17213108.

[26] S. Dorel, M. G. Osman, C. V. Strejoiu, and G. Lazaroiu, "Exploring optimal charging strategies for off-grid solar photovoltaic systems: A comparative study on battery storage techniques," *Batteries*, vol. 9, no. 9, pp. 470, 2023, doi: 10.3390/batteries9090470.

[27] M. Siregar, C. H. Pardosi, K. O. Bachri, T. Nur, and L. W. Pandjaitan, "Comparison of actual results and PVSyst simulation in the design of off-grid solar power generation system (PLTS) in Karuni Village, Southwest Sumba," *Jurnal Elektro*, vol. 17, no. 1, pp. 1-12, 2024, doi: 10.25170/jurnalelektro.v17i1.5419.
[28] I. N. Zhafarina, "Developing a 6-kilowatt-peak off-grid solar power station (PLTS) at the Az-Zawiyah Foundation in Tanjung Batu, Ogan Ilir, South Sumatra," *VOLT: Jurnal Ilmiah Pendidikan Teknik Elektro*, vol. 9, no. 1, pp. 9-21, 2024, doi: 10.30870/volt.v9i1.24439.
[29] A. Boudaoud, M. A. Atillah, H. Stitou, and M. Aqil, "Power performance analysis in off-grid photovoltaic battery system with ANFIS-FL based MPPT under partial shading effects," *Nigerian Journal of Technological Development*, vol. 22, no. 5, pp. 196-209, 2025, doi: 10.63746/njtd.v22i5.3640.
[30] R. P. Prastio, P. Megantoro, S. Arifin, I. R. Mutiarso, A. R. Muzadi, F. B. Firmansyah, and S. D. Perkasa, "The utilization of 900 Wp off-grid solar power plant for product intensification of a hydroponics farmer group," *Jurnal Pengabdian dan Pemberdayaan Masyarakat Indonesia*, vol. 2, no. 8, pp. 302-308, 2022, doi: 10.59247/jppmi.v2i8.128.
[31] Y. T. Wassie, and E. O. Ahlgren, "Performance and reliability analysis of an off-grid PV mini-grid system in rural tropical Africa: A case study in southern Ethiopia," *Development Engineering*, vol. 8, pp. 100106, 2023, doi: 10.1016/j.deveng.2022.100106.
[32] R. Naresh, S. K. Jadav, M. Singh, A. Patel, B. Singh, S. Beese, and S. K. Pandey, "Role of hydroponics in improving water-use efficiency and food security," *International Journal of Environment and Climate Change*, vol. 14, no. 2, pp. 608-633, 2024, doi: 10.9734/IJECC/2024/v14i23976.
[33] M. K. Khan, M. H. Zafar, T. Riaz, M. Mansoor, and N. Akhtar, "Enhancing efficient solar energy harvesting: a process-in-loop investigation of MPPT control with a novel stochastic algorithm," *Energy Conversion and Management: X*, vol. 21, pp. 100509, 2024, doi: 10.1016/j.ecmx.2023.100509.
[34] M. L. Katche, M. L., Makokha, A. B., Zachary, S. O., & Adaramola, M. S. (2023). A comprehensive review of maximum power point tracking (mppt) techniques used in solar pv systems. *Energies*, *16*(5), 2206, 2023, doi: 10.3390/en16052206.
[35] S. J. Yaqoob, H. Arnoos, N. T. Alwan, M. Bajaj, I. M. Alwan, M. H. A. Aljanabi, and M. S. Geremew, "Advanced maximum power point tracking in photovoltaic systems: A comprehensive review of classical, ai-based, and metaheuristic optimization techniques," *Engineering Reports*, vol. 7, no. 9, pp. e70404, 2025, doi: 10.1002/eng2.70404.
[36] M. A. Abdelhamid, T. K. Abdelkader, H. A. Sayed, Z. Zhang, X. Zhao, and M. F. Atia, "Design and evaluation of a solar powered smart irrigation system for sustainable urban agriculture," *Scientific Reports*, vol. 15, no. 1, pp. 11761, 2025, doi: 10.1038/s41598-025-94251-3.
[37] E. Villagran, J. J. Espitia, F. A. Velázquez, A. Sarmiento, D. A. S. Velandia, and J. Rodriguez, "Artificial intelligence in solar-assisted greenhouse systems: A technical, systematic and bibliometric review of energy integration and efficiency advances," *Technologies*, vol. 13, no. 12, pp. 574, 2025, doi: 10.3390/technologies13120574.
[38] K. Kim, and J. I. Choi, "Effect of cell-to-cell variation and module configuration on the performance of lithium-ion battery systems," *Applied Energy*, vol. 352, pp. 121888, 2023, doi: 10.1016/j.apenergy.2023.121888.
[39] F. J. Sepúlveda, I. Montero, F. Barrena, M. T. Miranda, and J. I. Arranz, "Design and energy analysis of photovoltaic-battery prototype considering different voltage levels," *Batteries*, vol. 9, no. 1, pp. 16, 2022, doi: 10.3390/batteries9010016.
[40] F. J. Sepúlveda, I. Montero, F. Barrena, M. A. Domínguez, and M. T. Miranda, "Efficiency evaluation of photovoltaic systems with batteries considering different voltage levels," *Journal of Energy Storage*, vol. 63, pp. 106971, 2023, doi: 10.1016/j.est.2023.106971.
[41] S. Manna, D. K. Singh, A. K. Akella, H. Kotb, K. M. AboRas, H. M. Zawbaa, and S. Kamel, "Design and implementation of a new adaptive MPPT controller for solar PV systems," *Energy Reports*, vol. 9, pp. 1818-1829, 2023, doi: 10.1016/j.egyr.2022.12.152.
[42] A. M. Eltamaly, Z. A. Almutairi, and M. A. Abdelhamid, "Modern optimization algorithm for improved performance of maximum power point tracker of partially shaded PV systems," *Energies*, vol. 16, no. 13, pp. 5228, 2023, doi: 10.3390/en16135228.
[43] L. Zemite, J. Kozadajevs, L. Jansons, I. Bode, E. Dzelzitis, and K. Palkova, "Integrating renewable energy solutions in small-scale industrial facilities," *Energies*, vol. 17, no. 11, pp. 2792, 2024, doi: 10.3390/en17112792.
[44] N. Alfred, V. Guntreddi, A. N. Shuaibu, and M. S. Bakare, "A fuzzy logic based energy management model for solar PV-wind standalone with battery storage system," *Scientific Reports*, vol. 15, no. 1, pp. 24660, 2025, doi: 10.1038/s41598-025-09662-z.
[45] S. Khan, K. Sudhakar, M. H. Yusof, and S. Sundaram, "Review of building integrated photovoltaics system for electric vehicle charging," *The Chemical Record*, vol. 24, no. 3, pp. 202300308, 2024, doi: 10.1002/tcr.202300308.
[46] H. A. Helmy, A. M. El-Rifaie, A. A. Youssef, A. Haggag, H. Hamad, and M. Eltokhy, "Improving solar energy-harvesting wireless sensor network (SEH-WSN) with hybrid Li-Fi/Wi-Fi, integrating markov model, sleep scheduling, and smart switching algorithms," *Technologies*, vol. 13, no. 10, pp. 437, 2025, doi: 10.3390/technologies13100437.
[47] L. Shi, Y. Liu, C. Sun, Y. Guo, D. Wang, Y. Liu, and C. Wang, "Energy solution for rural household in remote cold regions: An innovative photovoltaic-based thermal energy storage system," *Energy Conversion and Management*, vol. 343, pp. 120216, 2025, doi: 10.1016/j.enconman.2025.120216.
[48] S. I. Orakwue, H. M. R. Al-Khafaji, V. C. Ikenyiri, and V. C. Godson, "Solar powered automated hydroponic farming system with iot feedback," *Journal of Information Technology Management*, vol. 14, no. 3, pp. 26-38, 2022, doi: 10.22059/JITM.2022.87261.
[49] Y. Islamiati, and T. Dewi, "IoT monitoring for solar powered pump applied in hydroponic house," *International Journal of Research in Vocational Studies (IJRVOCAS)*, vol. 2, no. 2, pp. 22-30, 2022, doi: 10.53893/ijrvocas.v2i2.102.

[50] A. S. Alqahtani, A. Mubarakali, P. Parthasarathy, G. Mahendran, and U. A. Kumar, "Retracted article: Solar PV fed brushless drive with optical encoder for agriculture applications using IoT and FPGA," *Optical and Quantum Electronics*, vol. 54, no. 11, pp. 715, 2022, doi: 10.1007/s11082-022-04065-0.

[51] Nejatian, A., Niane, A. A., Makkawi, M., Al-Sham'aa, K., Shamsi, S. A. R. A., Naqbi, T. S. A. M. A., ... & Juma, J. E. (2025). Solar-Powered RO–Hydroponic Net House: A Scalable Model for Water-Efficient Tomato Production in Arid Regions. *Sustainability*, *17*(24), 11298, 2025, doi: 10.3390/su172411298.