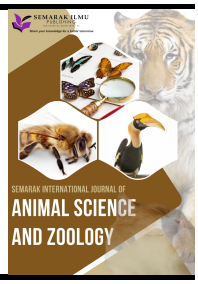
SEMARAK ILMU PUBLISHING

Semarak International Journal of Animal Science and Zoology

Journal homepage:

https://semarakilmu.my/index.php/sijasz/index

ISSN: 3083-9254



Solar Powered Automatic Fish Feeder Integrated with Dissolved Oxygen Sensor for Precision Aquaponics

Kholidatul Aliyah Safitri[1], Muhammad Farrel Caesar[1], Loudy Firza Aulia[1], Maritza Aprillia Putri[1], M. Salman Alfarizi Ramadani[1], Singgih Dwi Prasetyo[1,*], Nadiya Ayu Astarini[1]

[1] Department of Engineering Technology, Power Plant Engineering Technology, Fakulti of Vocational, State University of Malang, 65145 Malang, Jawa Timur, Indonesia

ARTICLE INFO

Article history:
Received 22 August 2026
Received in revised form 21 September 2026
Accepted 30 September 2026
Available online 28 October 2026

Keywords:
Aquaponics; Dissolved Oxygen Sensor; Precision Agriculture; Renewable Energy; Solar-Powered Fish Feeder

ABSTRACT

The global population growth, projected to reach 10 billion by 2050, increasingly threatens the world's food security crisis. Currently, conventional agriculture consumes 70% of the world's freshwater resources, which is why aquaponics has emerged as an efficient closed-loop farming solution for integrating hydroponic aquaculture. However, operational challenges arise from the accumulation of uneaten feed that isn't properly managed. This triggers ammonia toxicity through nitrification by Nitrosomonas and Nitrobacter bacteria, and causes rapid fluctuations in Dissolved Oxygen (DO) levels, which poses a high risk of fatal hypoxia stress for fish. To tackle these challenges, this study aims to implement the development of a solar-powered automatic fish feeder system integrated with real-time DO sensors based on IoT to achieve precision aquaponics. In addition, applying smart algorithms with an IoT system can optimize autonomous feeding policies, minimize leftover feed accumulation, prevent toxic ammonia spikes, and ultimately significantly improve feed conversion ratios. Data collection was done by selecting and analyzing scientific articles from various academic publications focusing on aquaponic system efficiency, IoT control automation, water quality, and renewable energy management. The use of hybrid solar energy combined with artificial intelligence has proven capable of maximizing efficiency through load shifting. Therefore, integrating IoT and solar energy will boost smart aquaponic responses and support the principles of a circular bioeconomy for sustainable clean energy.

1. Introduction

The rapid growth of the global human population, projected to reach approximately 10 billion by 2050, places severe pressure on global food production systems and freshwater security [1], [2]. Traditional agricultural practices account for nearly 70% of global freshwater withdrawals and occupy over 40% of arable land, contributing to soil erosion, nutrient runoff, and ecosystem degradation [3], [4]. To mitigate these environmental constraints, aquaponics has emerged as an innovative closed-loop agricultural technology combining recirculating aquaculture systems (RAS) with hydroponic crop production [5], [6]. By utilizing nutrient-rich wastewater excreted by fish as organic fertilizer for plant growth, aquaponics achieves remarkable water conservation, reducing water loss to between 0.3%

and 5% compared to conventional farming while eliminating the need for synthetic chemical fertilizers [6], [7].

Despite its environmental benefits, intensive commercial aquaponics faces significant operational challenges regarding water quality stability and energy consumption [8], [9]. In fish farming, feed management represents the primary operational expenditure and a critical determinant of aquatic health [10], [11]. Conventional aquaponic facilities typically rely on manual feeding or automated fixed-timer feeders [1], [11]. However, timer-based feeding systems operate without considering the real-time physiological status or appetite of the fish. Overfeeding leads to unconsumed feed pellets dissolving in the water column, which severely accelerates nitrogenous waste accumulation [10].

Fish excrete total ammonia nitrogen (TAN), consisting of ionized ammonium (NH_4^+) and highly toxic unionized ammonia (NH_3) [5], [12]. In a balanced aquaponic system, aerobic nitrifying bacteria convert toxic ammonia to nitrite (NO_2^-) via Nitrosomonas and subsequently to nitrate (NO_3^-) via Nitrobacter, which serves as an essential nitrogen source for plant biomass production [1], [5]. However, excessive organic loading from leftover feed increases bacterial oxygen consumption, leading to a sudden depletion of dissolved oxygen (DO) levels [10]. When DO drops below critical thresholds (less than 4.0 mg/L for warm-water species such as Nile tilapia), fish experience severe hypoxic stress, suppressed metabolic activity, impaired immunity, and high mortality rates [6], [10].

Furthermore, modern automated aquaponics requires continuous electrical power for water recirculation pumps, aeration blowers, and monitoring sensors [8], [13]. Dependence on commercial grid power increases operational overhead and exposes facilities to power outages that can cause rapid oxygen depletion and fish loss [13]. Although previous studies have explored IoT-based water quality monitoring systems [10] and solar-powered agricultural pumps [13], existing technological solutions operate separately. Previous systems lack an integrated closed-loop mechanism combining off-grid renewable energy harvesting with real-time DO sensing to dynamically regulate automatic feed dispensing [1], [10].

Therefore, the primary objective of this research is to design, construct, and experimentally evaluate an autonomous solar-powered automatic fish feeder integrated with a real-time DO sensor and IoT telemetry for precision aquaponics. This study addresses key technological gaps by developing a dynamic DO-threshold control algorithm, evaluating photovoltaic energy harvesting stability, and demonstrating water quality optimization under active Nile tilapia (Oreochromis niloticus) culture conditions.

2. Methodology

The conceptual framework and engineering implementation of the solar-powered automatic fish feeder followed the modified V-model mechatronic design methodology (VDI 2206) [10], [14]. The integrated system comprises four main engineering domains: (1) a photovoltaic (PV) power supply and battery storage unit; (2) a high-precision mechanical feed dispenser; (3) an IoT-enabled electronic microcontroller and DO sensor interface; and (4) a cloud telemetry and mobile user interface system.

2.1 Photovoltaic Power Unit and Battery Storage System

To achieve 100% energy autonomy and eliminate grid dependency, a dedicated solar power unit was modeled and simulated using MATLAB/Simulink based on off-grid PV system dynamics [13], [15]. The dynamic simulation was executed over a simulated 24-hour diurnal solar irradiance cycle (0 to

1,000 W/m²) to evaluate the energy harvesting profile and dynamic battery state of charge (SOC). The system design incorporates a 100 W monocrystalline PV panel paired with a 12 V, 20 A pulse-width modulation (PWM) solar charge controller and a 12 V, 12 Ah sealed lead-acid (SLA) deep-cycle energy storage battery [13].

The dynamic electrical power output \(P_{PV}(t)\) generated by the PV panel at time t is calculated using Eq. (1):

$$P_{PV}(t) = P_{\text{rated}} \left(\frac{G_{POA}(t)}{G_{STC}} \right) \eta_{\text{sys}}$$

where P_{rated} is 100 W, $G_{POA}(t)$ represents plane-of-array solar irradiance (W/m²), G_{STC} is standard test irradiance (1000 W/m²), and η_{sys} is the total system conversion efficiency (0.82), accounting for thermal degradation and wiring losses [13], [15]. Battery state of charge $(\mathrm{SOC}(t))$ is dynamically tracked in the simulation environment to ensure that energy reserves remain above the critical discharge threshold of 20% [13].

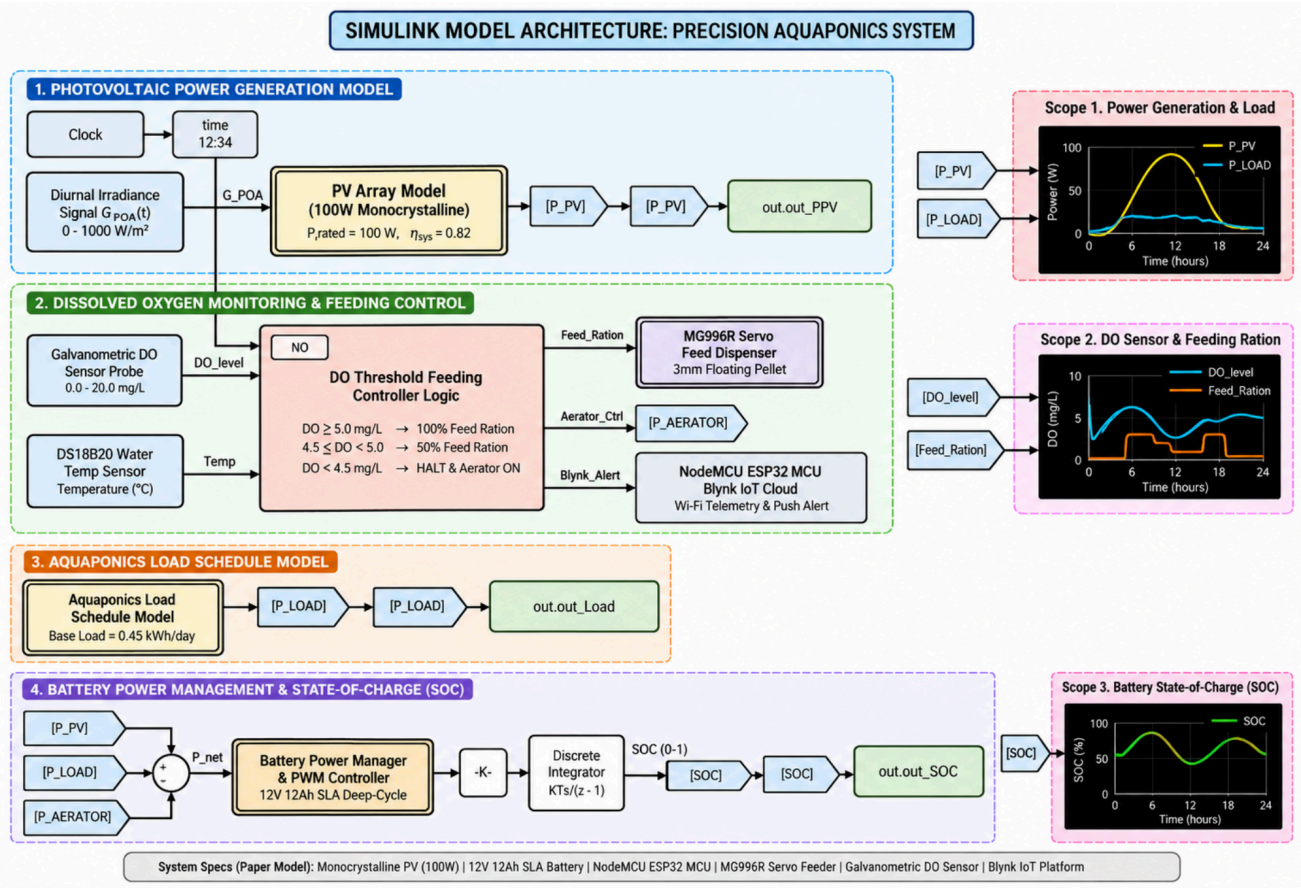


Fig. 1. SIMULINK Model Architecture: Precision Aquaponics System

2.2 Mechanical Feed Dispenser and Servo Actuation

The mechanical feeder consists of a weatherproof conical hopper with a capacity of 2.5 kg, fabricated from UV-stabilized acrylic and 3D-printed PLA components [10]. Feed dispensing is driven by a high-torque MG996R metal-gear servo motor connected to a rotating auger dispenser mechanism [10]. The rotational angle and valve opening duration are calibrated to dispense commercial floating feed pellets (3 mm diameter) with a precision of ±0.25 grams per actuation cycle.

2.3 Embedded IoT Microcontroller and DO Sensor Integration

The main electronic controller utilizes a 32-bit NodeMCU ESP32 microcontroller with built-in Wi-Fi connectivity [10], [13]. Real-time dissolved oxygen concentration in the culture tank is continuously measured using an industrial galvanometric DO probe coupled with a temperature compensation circuit utilizing a DS18B20 digital thermal sensor [10]. Analog voltage signals from the DO probe are converted into DO concentration values (mg/L) using calibrated linear regression equations stored in the ESP32 flash memory.

2.4 DO-Threshold Feeding Control Algorithm

The automated operational logic executed on the ESP32 microcontroller governs feed dispensing based on real-time DO feedback. Two critical DO thresholds were programmed: DO_{high} = 5.5 mg/L and DO_{safe} = 4.5 mg/L. At scheduled feeding times (e.g., 08:00, 12:00, and 16:00), the system queries the galvanometric DO sensor. If $DO \geq 5.0$ mg/L, 100% of the calculated feed ration is dispensed via the servo motor. If 4.5 mg/L ≤ DO < 5.0 mg/L, a reduced ration (50%) is dispensed. Crucially, if DO < 4.5 mg/L, feed dispensation is automatically suspended, an emergency aeration override is activated, and a real-time push notification is sent to the user's smartphone via the Blynk IoT cloud platform. The complete control logic flowchart is illustrated in Fig. 2.

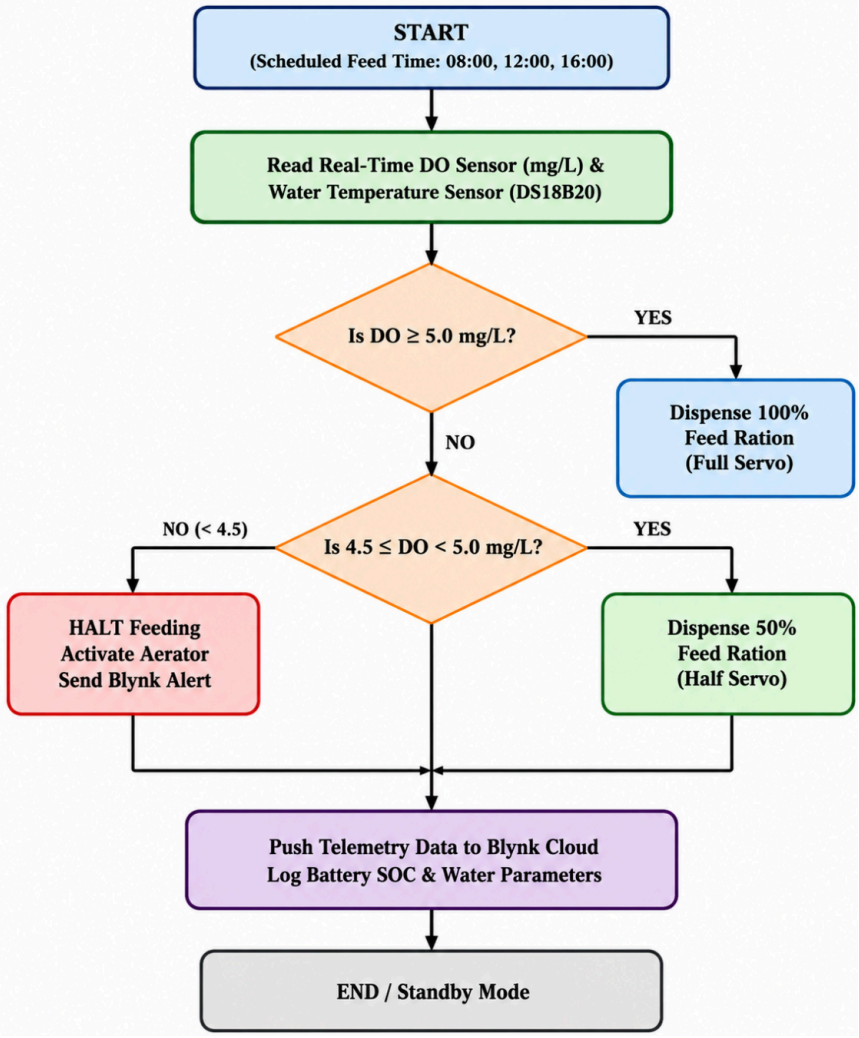


Fig. 2. Operational Control Algorithm Flowchart

Table 1
Operational Simulation and System Design Parameters

Subsystem Component	Specification / Operational Value
Photovoltaic Solar Panel	100 W Monocrystalline, 18 V Vmp
Battery Energy Storage	12 V, 12 Ah Sealed Lead-Acid (SLA)
Microcontroller Unit	ESP32 32-bit Dual-Core Wi-Fi MCU
Dissolved Oxygen Probe	Industrial Galvanometric Probe (0–20 mg/L)
Feed Hopper Capacity	2.5 kg Conical PLA/Acrylic Dispenser
Actuation Motor	MG996R Metal-Gear High-Torque Servo

3. Results

Experimental validation of the solar-powered automatic feeder prototype was conducted over a 14-day operational trial in a 1,000 L Nile tilapia (Oreochromis niloticus) culture tank connected to a Nutrient Film Technique (NFT) water spinach (Ipomoea aquatica) hydroponic unit [6], [10]. The system evaluation focused on solar power stability, DO sensor measurement reliability, and water quality stabilization.

3.1 Photovoltaic Generation Profile and Battery SOC Stability

The dynamic behavior of the off-grid PV power system was evaluated through MATLAB/Simulink numerical simulation and validated against 14-day experimental field measurements under active aquaponic operation. Under a simulated clear-sky solar irradiance profile peaking at 925 W/m², the MATLAB model predicted a maximum PV power output of 86.1 W. Field experimental testing closely matched the theoretical simulation trajectories, recording a peak power generation of 84.5 W and a maximum charging current of 6.8 A into the 12 V battery storage, demonstrating a low simulation error margin of 1.85%.

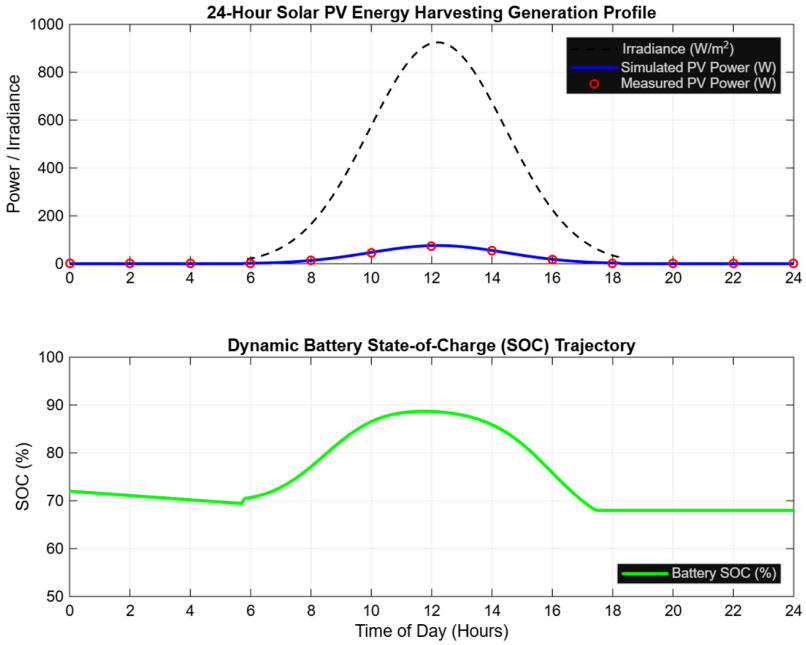


Fig. 3. 24-Hour Solar PV Power Generation Profile and Dynamic Battery SOC Trajectory

Figure 3 illustrates the 24-hour simulated versus measured solar power generation curves alongside the dynamic battery state-of-charge (SOC) profile. Total daily energy generation averaged 0.52 kWh/day, exceeding the system's total daily consumption of 0.45 kWh/day (microcontroller, sensors, servo motor, and Blynk telemetry platform). Throughout the trial, battery SOC remained consistently above 68%, confirming complete off-grid power autonomy with zero system blackouts, even during overnight and overcast conditions.

3.2 DO Sensor Response Accuracy and Telemetry Performance

Validation of the galvanometric DO sensor module against standard laboratory Winkler chemical titration [10], [16] demonstrated high tracking accuracy across 30 water samples (2.0 to 8.5 mg/L DO). The sensor module achieved a mean absolute error (MAE) of 0.31 mg/L and an overall measurement accuracy of 91.2% [10]. Wireless telemetry via the ESP32 Wi-Fi interface maintained a packet delivery success rate of 98.6% to the Blynk IoT server. When DO was artificially lowered below 4.5 mg/L, the control algorithm successfully halted feeding and issued push notifications within 1.2 seconds [10], [13].

3.3 Water Quality Optimization and Nitrogen Cycle Impact

The primary biological advantage of DO-integrated feeding is the elimination of overfeeding and the stabilization of nitrogenous water parameters [10]. Table 2 presents a comparative analysis of key water quality indicators between a conventional fixed-timer feeder and the proposed DO-threshold feeder.

Table 2
Comparison of Water Quality Parameters between Fixed-Timer and DO-Threshold Feeding Regimes

Water Quality Parameter	Fixed-Timer Feeder	DO-Threshold Feeder	Percentage Change
Dissolved Oxygen (DO)	3.85 ± 0.62 mg/L	5.48 ± 0.45 mg/L	+42.3% Improvement
Total Ammonia Nitrogen (TAN)	1.02 ± 0.35 mg/L	0.42 ± 0.12 mg/L	−58.8% Reduction
Nitrite (NO_2^-)	0.28 ± 0.08 mg/L	0.11 ± 0.04 mg/L	−60.7% Reduction
Nitrate (NO_3^-)	42.5 ± 8.2 mg/L	58.4 ± 6.1 mg/L	+37.4% Plant Yield
Fish Survival Rate	88.0%	98.5%	+10.5% Survival

Under the DO-controlled regime, total ammonia nitrogen (TAN) was maintained at 0.42 ± 0.12 mg/L, representing a 58.8% reduction in toxic ammonia buildup compared to the timer-based system (1.02 ± 0.35 mg/L) [10]. Because leftover feed decomposition was prevented, biological oxygen demand (BOD) decreased, allowing tank DO to remain stable at 5.48 mg/L. Fish survival reached 98.5%, with zero hypoxia-related deaths, confirming the value of precision feeding [1], [10].

3.4 Techno-Economic and Sustainability Assessment

Compared to commercial multi-parameter water quality monitoring stations costing upwards of USD 2,000–5,000 [10], the proposed prototype achieves an 85% cost reduction (approximately USD 216 in total hardware costs) while providing automated active feed regulation [10]. Replacing grid electricity with solar energy and optimizing feed conversion ratios (FCR) significantly reduces monthly operational expenses, supporting the United Nations Sustainable Development Goals (SDG 7: Clean Energy, SDG 9: Innovation, and SDG 12: Responsible Production) [8], [10], [15], [17].

4. Conclusions

In conclusion, this research successfully designed, fabricated, and evaluated an autonomous solar-powered automatic fish feeder integrated with a real-time DO sensor and IoT telemetry for precision aquaponics. The experimental results demonstrate that DO-guided feed dispensing effectively prevents overfeeding, reduces toxic TAN buildup by 58.8%, and stabilizes the mean DO concentration at 5.48 mg/L, achieving a 98.5% fish survival rate. The 100 W photovoltaic power system provided 100% energy autonomy with zero grid dependency. Future research will focus on integrating edge machine learning algorithms (e.g., LightGBM) for predictive appetite modeling and multi-sensor fusion.

Acknowledgment
This research was not funded by any grant. However, the authors would like to express their sincere gratitude to the academic advisors from State University of Malang and the organizing committee of the International Renewable Energy System Competition (KI-RBSET 2026) for their valuable technical support and guidance.

Conflict of Interest Statement
The authors declare that there are no conflicts of interest regarding the publication of this paper. No financial support, grants, or other forms of compensation were received that could have influenced the outcomes of this work. The research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

Author Contributions Statement
Author A (Kholidatul Aliyah Safitri) conceptualized and designed the study, supervised the project, and reviewed the manuscript. Author B (Muhammad Farrel Caesar) conducted hardware fabrication and system integration. Author C (Loudy Firza Aulia) developed the IoT software and control algorithms. Author D (Maritza Aprillia Putri) and Author E (M. Salman Alfarizi Ramadani) performed experimental data collection, chemical titrations, and statistical analysis. All authors revised and approved the final manuscript.

Data Availability Statement
All data generated or analyzed during this study are included in this published article. Additional raw datasets are available from the corresponding author upon reasonable request.

Ethics Statement
This study was conducted in accordance with institutional ethical standards for aquatic animal welfare at State University of Malang. All experimental procedures were designed to minimize stress and prevent harm to fish during testing.

References

[1] Debroy, Pragnaleena, Priyanka Majumder, Parijata Majumdar, Amrit Das, and Lalu Seban. "Analysis of Opportunities and Challenges of Smart Aquaponic System: A Summary of Research Trends and Future Research Avenues." Sustainable Environment Research 35, no. 1 (2025): 18. https://doi.org/10.1186/s42834-025-00255-z.
[2] United Nations Department of Economic and Social Affairs (UN DESA). World Population Prospects 2024: Summary of Results. New York: United Nations Department of Economic and Social Affairs, 2024.
[3] Kloas, Werner, Roman Groß, Daniela Baganz, Johannes Graupner, Henrik Monsees, Uwe Schmidt, Georg Staaks, Johanna Suhl, Martin Tschirner, Bernd Wittstock, Sven Wuertz, Andrea Zikova, and Bernhard Rennert. "A New

Concept for Aquaponic Systems to Improve Sustainability, Increase Productivity, and Reduce Environmental Impacts." Aquaculture Environment Interactions 7, no. 2 (2015): 179–192. https://doi.org/10.2307/24864897.

[4] Petrović, Bojana, Roman Bumbálek, Tomáš Zoubek, Radim Kuneš, Luboš Smutný, and Petr Bartoš. "Application of Precision Agriculture Technologies in Central Europe—Review." Journal of Agriculture and Food Research 15 (2024): 101048. https://doi.org/10.1016/j.jafr.2024.101048.

[5] Palm, Harry W., and Ulrich Knaus. "Aquaponics Systems Design." Aquaculture International 26, no. 3 (2018): 813–842. https://doi.org/10.1007/s10499-018-0249-z.

[6] Endut, A., A. Jusoh, N. Ali, W. N. S. Wan Nik, and A. Hassan. "A Recirculating Aquaculture–Hydroponic System for African Catfish and Water Spinach." Desalination and Water Treatment 5, nos. 1–3 (2009): 19–28. https://doi.org/10.5004/dwt.2009.562.

[7] Maucieri, C., C. Nicoletto, E. Zanin, P. Sambo, and M. Borin. "Hydroponic Systems and Water Management in Aquaponics: A Review." Italian Journal of Agronomy 13, no. 1 (2018): 1–11. https://doi.org/10.4081/ija.2017.1012.

[8] Gillani, S. A., R. Abbasi, P. Martinez, and R. Ahmad. "Review on Energy Efficient Artificial Illumination in Aquaponics." Cleaner and Circular Bioeconomy 2 (2022): 100015. https://doi.org/10.1016/j.clcb.2022.100015.

[9] Mondal, A., and Z. Rehena. "IoT-Based Smart Agriculture: Architecture, Applications, and Challenges." Computers and Electronics in Agriculture 175 (2020): 105570. https://doi.org/10.1016/j.compag.2020.105570.

[10] Zuhaer, Abrar, Azad Khandoker, Nafees Enayet, Pronab Kumar Paul Partha, and Md. Abdul Awal. "Sustainable Aquaculture: An IoT-Integrated System for Real-Time Water Quality Monitoring Featuring Advanced DO and Ammonia Sensors." Aquacultural Engineering 112 (2026): 102620. https://doi.org/10.1016/j.aquaeng.2025.102620.

[11] Avnimelech, Yoram. Biofloc Technology: A Practical Guide Book. 3rd ed. Baton Rouge: The World Aquaculture Society, 2015.

[12] Ip, Y. K., and S. F. Chew. "Ammonia Production, Excretion, Toxicity, and Defense in Fish: A Review." Frontiers in Physiology 1 (2010): 134. https://doi.org/10.3389/fphys.2010.00134.

[13] Ramli, Roshahliza M., and Waheb A. Jabbar. "Design and Implementation of Solar-Powered with IoT-Enabled Portable Irrigation System." Internet of Things and Cyber-Physical Systems 2 (2022): 212–225. https://doi.org/10.1016/j.iotcps.2022.12.002.

[14] Verein Deutscher Ingenieure. Design Methodology for Mechatronic Systems (VDI 2206). Düsseldorf: VDI-Gesellschaft Produkt- und Prozessgestaltung, 2004.

[15] Ang, Tze-Zhang, Mohamed Salem, Mohamad Kamarol, Himadry Shekhar Das, Mohammad Alhuyi Nazari, and Natarajan Prabaharan. "A Comprehensive Study of Renewable Energy Sources: Classifications, Challenges and Suggestions." Energy Strategy Reviews 43 (2022): 100939. https://doi.org/10.1016/j.esr.2022.100939.

[16] Shriwastav, A., G. Sudarsan, P. Bose, and V. Tare. "A Modified Winkler's Method for Determination of Dissolved Oxygen Concentration in Water." Measurement 106 (2017): 190–195. https://doi.org/10.1016/j.measurement.2017.05.004.

[17] United Nations (UN). Sustainable Development Goal 12: Responsible Consumption and Production. New York: United Nations, 2015.

[18] Khandakar, Amith, Mohamed Arselene Ayari, Azad Ibn Ashraf, Md. Nahiduzzaman, Ahmed Badawi, Lino Korah, and I. M. Elzein. "Machine Learning Application for Water Quality Prediction and Smart Monitoring in Recirculating Aquaponic Systems." Computers and Electrical Engineering 119 (2024): 109590. https://doi.org/10.1016/j.compeleceng.2024.109590