



SQCDM analysis for pv and vawt-based smart aquaponic systems

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ABSTRACT

Background: Rapid urbanization, climate stress, and resource limitations increase the need for resilient urban food production systems. Aquaponics offers a sustainable approach by integrating aquaculture and hydroponics, but challenges remain in environmental monitoring, operational efficiency, and energy reliability. Emerging technologies such as IoT, AI, automation, and renewable energy can enhance system performance. **Methods:** This study develops a conceptual design of a grid-aware smart aquaponics system through a literature review and practice-grounded system description. The proposed architecture integrates IoT-based water quality sensing, AI-assisted plant monitoring, automated feeding, a Fuzzy Logic Controller on a Raspberry Pi 4, and a hybrid photovoltaic-vertical-axis wind turbine (PV-VAWT) power supply. The design is evaluated using the SQCDM framework (Safety, Quality, Cost, Delivery, and Morale). **Findings:** The proposed system enables continuous monitoring and feedback control of water quality parameters, supports fish and plant health, reduces routine labor through automation, and ensures uninterrupted operation through hybrid renewable energy. The SQCDM assessment highlights enhanced operational safety, quality assurance through real-time monitoring, cost transparency, deployment feasibility using off-the-shelf components, and improved user confidence through accessible interfaces and training support. **Conclusion:** The conceptual architecture provides a practical framework for future smart aquaponics implementation. The integration of cyber-physical supervision, intelligent control, and renewable energy has the potential to improve system resilience, operational stability, and sustainability in urban food production. **Novelty/Originality of this article:** This study proposes an integrated grid-aware smart aquaponics framework that combines IoT sensing, AI-based crop assessment, fuzzy logic control, automated feeding, and hybrid PV-VAWT renewable energy. It also introduces the SQCDM framework as a comprehensive and practice-oriented tool for evaluating smart aquaponics system design and operational readiness.

KEYWORDS: aquaponics; internet of things; renewable energy; SQCDM.

1. Introduction

Food plays a central role in sustaining human life and national stability. Between 713 and 757 million people (approximately 9% of the world's population) suffered from hunger in 2023, a trend that has been increasing since 2019, indicating that conventional food systems are highly vulnerable to global disruptions (FAO et al., 2024). Population growth and urbanization in major cities around the world have triggered a surge in global energy demand. Total global primary energy demand in 2023 is expected to reach approximately

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620 EJ (exajoules), and is projected to continue increasing in line with economic growth, industrialization, and the electrification of transportation and global digitalization (World Economic Forum, 2024; S&P Global, 2024). The proportion of renewable energy in each country's primary energy consumption in Fig. 1. Shows that countries such as Norway, Brazil, and New Zealand have achieved more than 60% renewable energy mix, while most countries in Asia, Africa, and the Middle East are still below 20%, reflecting a huge disparity in the global energy transition.

The converging crises of food, climate, and energy demand a cross-disciplinary response that couples sustainable food production, efficient renewable power, and intelligent automation. The IPCC's latest synthesis underscores how persistent warming amplifies weather extremes, shifts rainfall patterns, and raises agricultural uncertainty, especially across tropical regions, requiring system-level adaptation and water-energy efficiency improvements in production systems (Calvin et al., 2023). At the same time, the cost and accessibility of healthy diets remain problematic: recent analyses estimate that nutrient-adequate food baskets are still unaffordable for hundreds of millions of low-income households, aggravating malnutrition and household food insecurity across developing economies (Headey et al., 2024).

Traditional aquaculture/aquaponics often relies on manual inspection, periodic laboratory sampling, fixed-schedule aeration/feeding, and simple set-point control. This approach introduces detection latency when ammonia or nitrite spikes or when dissolved oxygen (DO) dips, delaying corrective actions, worsening feed conversion ratio (FCR), and elevating mortality risk (Brown et al., 2025). Technical reviews further highlight that maintaining water quality in recirculating aquaculture systems (RAS) is most challenging in managing suspended solids, reactive nitrogen, and biofilter dynamics, manual workflows increase observer bias and inter-operator variability (Brown et al., 2025). In aquaponics specifically, bio-techno surveys emphasize the delicate balance among stocking density, carbon-to-nitrogen (C:N) ratio, fish-to-plant feed balance, and dependable sensing to keep nitrification-denitrification stable, without automation, downtime and under/overfeeding are common (Krastanova et al., 2022). Economic and organizational analyses add that profitability, technical literacy, and regulatory/labeling uncertainties, especially when dependent on costly or unstable grid electricity have constrained adoption at small and medium scales (Okomoda et al., 2023). The sector therefore needs a leap toward continuous sensor-based monitoring, predictive control, and on-site renewable power for critical loads. Shifting from reactive to data-driven preventive operation can shrink week-to-week water-quality variance, improve fish and plant growth consistency, and cut operating expenses, especially energy for aeration and pumping without compromising biosecurity (Brown et al., 2025; Krastanova et al., 2022; Okomoda et al., 2023). Aquaponics-based urban farming provides an alternative for sustainable food production in urban areas through the efficient use of limited space and resources, and can be optimized using smart aquaponics systems to improve the effectiveness of monitoring, environmental management, and crop yields with precision (Insigne & Balba, 2024). Limited land in urban areas has encouraged innovation in urban farming that focuses on local food production, especially fish and vegetables. Demand for organic food in cities is increasing, reflected in the growing number of consumers who are aware of the importance of healthy eating and environmental sustainability. Aquaponics systems, which combine aquaculture and hydroponics, have gained attention as a technological solution that can improve space utilization efficiency and optimize production in urban environments (Boukharta et al., 2025; Fei et al., 2025; Hemerijckx et al., 2025).

Global research shows that the adoption of aquaponics systems continues to increase in various countries, driven by space and water efficiency and food yield advantages, especially in urban areas with limited land (Basumatary et al., 2023). Aquaponics is an agricultural technology that combines fish farming (aquaculture) and plant cultivation (hydroponics) in a closed cycle, where organic waste from fish is converted by bacteria into nutrients that can be absorbed by plants, while plant roots purify the water that returns to

the fish pond. The entire cycle runs continuously with the support of aeration and water quality monitoring (Spradlin & Saha, 2022).

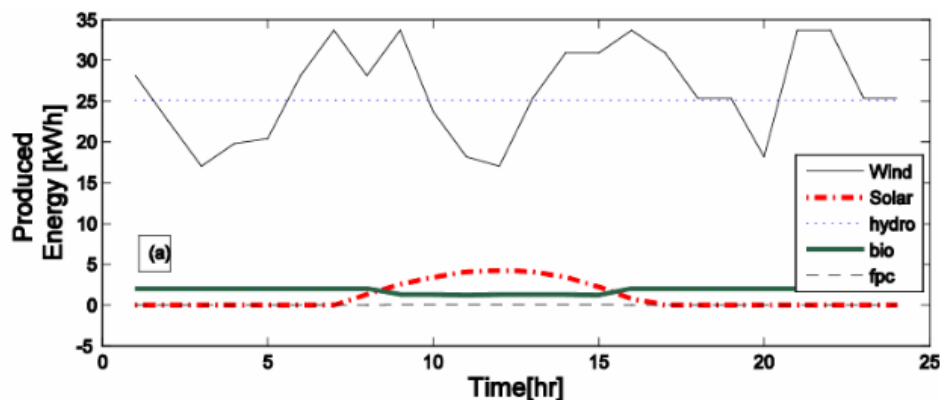


Fig. 1. Allocation of energy produced to/from the battery/grid. (Karimanzira & Rauschenbach, 2018).

The system has been proven to save up to 90% of water compared to conventional agriculture, accelerate plant and fish growth and productivity in limited spaces, and reduce waste and the need for chemical fertilizers (Dewi et al., 2025). The integration of the Internet of Things (IoT) and sensors enables monitoring to ensure that every parameter is always optimal for the fish and plant ecosystem. Aquaponics still relies on a stable energy supply for pumps and aerators, so the use of renewable energy is needed to keep the system running in an energy-efficient and environmentally friendly manner (Dewi et al., 2025). Wind turbines in aquaponics systems serve as the primary energy source capable of maintaining a stable electricity supply when solar panels are not optimal, especially at night or during bad weather (Channa et al., 2025). Fig. 1. Shows that hourly electricity production from wind turbines varies between 15 and 35 kWh throughout the day, while the maximum contribution of solar energy occurs at midday at around 5 kWh per hour, and hydro, bio, and flat plate collector sources tend to be constant at below 5 kWh per hour, indicating that wind turbines are the dominant and most fluctuating energy source in the renewable energy hybrid scenario for aquaponics systems (Karimanzira & Rauschenbach, 2018). Research results show that vertical hybrid wind turbines generate twice as much power as conventional types and have much better self-start capabilities at low wind speeds (Seifi Davari et al., 2025). Energy capture efficiency reaches 0.23, far exceeding that of pure lift or drag turbines (Zhang et al., 2023). Climate change increases the risk of food scarcity, and Asia faces sustainable energy challenges, making system innovation essential to support Sustainable Development Goals (SDGs) 2 and 7 in densely populated areas (Pickson et al., 2023).

Recent work shows a decisive convergence of IoT, control, and AI in aquaponics: low-cost IoT stacks now enable continuous monitoring and closed-loop control of pH, DO, temperature, EC, turbidity, and water level in small farms (Zamnuri et al., 2024). Reliable, low-complexity stabilization remains practical via PID + IoT architectures that maintain tight pH and temperature set-points with less operator intervention (Kok et al., 2024). To improve responsiveness and resilience, modular edge-computing nodes reduce latency and scale to 16+ sensing modalities while syncing to the cloud (Wan et al., 2022). Moving beyond heuristics, optimization-based mixers reach targets faster with less overshoot under constraints (Kobelski et al., 2024). A recent systematic review confirms rapid AI/IoT adoption but highlights scarce open datasets and inconsistent evaluation protocols that hinder benchmarking and transfer (Anila & Daramola, 2024). Hybrid CAE+GRU models with metaheuristic feature weighting deliver robust water-quality prediction under noisy time-series signals (Sundararajan et al., 2025).

On the energy side, advances in PV—particularly perovskite–silicon tandems—have raised certified efficiencies and enabled more compact renewable layouts for urban and peri-urban facilities (Ašmontas & Mujahid, 2023). For wind, VAWTs are attractive where

space and turbulence are constraints: they are yaw-free, tolerant of multidirectional flows, can be low-profile on rooftops, and offer safety and acoustic advantages, even if average power coefficients are typically below those of HAWTs, diffuser-assisted, guide-vane, and counter-rotating designs have improved performance in recent prototypes (Didane et al., 2024). The PV + VAWT combination yields complementary production: PV dominates on clear days and during dry seasons, while VAWT provides coverage at night and in cloudy, windy conditions. When paired with modest battery storage, critical aquaponics loads (aeration, recirculation, dosing) can be maintained during grid outages. Microgrid sizing studies indicate that small hybrid solar-wind systems can reduce local energy cost, emissions, and grid dependence when sized against local weather and load data using well-posed optimization formulations (Merino & Castro, 2024). For SMEs and communities, modular configurations (rooftop PV plus building-mounted VAWTs) simplify retrofits without sacrificing growing area. Overall, this hybrid stack underpins always-on aquaponics with stable, low-cost energy, and lowers the carbon intensity of each kilogram of biomass produced.

Parallel advances target energy autonomy and operational efficiency: treating tanks and sumps as “hydraulic batteries” buffers pump duty cycles against PV intermittency and co-optimizes water logistics with energy use (Channa et al., 2025). MILP-style load scheduling aligns aeration/recirculation with tariff windows to cut costs without violating water-quality bounds (Zhao et al., 2024), and detailed energy modeling in large RAS offers transferable strategies for equipment sizing and duty-cycle control in aquaponics (Alnemari et al., 2025). Hybrid PV + micro-hydro supplies coupled with AI forecasting further increase self-sufficiency while stabilizing DO and temperature trajectories (Dewi et al., 2025). Beyond physicochemical sensing, YOLOv4-based vision quantifies fish locomotion as an early proxy for stress and water-quality anomalies (Liu et al., 2022), and adaptive-filter soft sensors estimate total nitrogen from easily measured signals to reduce dependence on lab assays (Li et al., 2021). Finally, end-to-end ML frameworks that combine attention mechanisms with hybrid learners optimize feeding and water exchange decisions, surpassing baseline LSTMs and pointing toward fully predictive operations (Chandramenon et al., 2024; Dhal et al., 2022; Elmessery et al., 2025; Khandakar et al., 2024).

Recent progress in perovskite-Si tandems has surpassed single-junction silicon efficiency limits while mitigating optical and non-radiative recombination via interface engineering, additives, and substrate texturing (Ašmontas & Mujahid, 2023). From a balance-of-system perspective, this translates to higher power density (W/m^2) critical for rooftop aquaponics and potentially lower levelized cost of electricity (LCOE) as manufacturing scales (Huang & Mao, 2025). In operation, onsite PV shifts electricity for aeration and pumping toward midday self-consumption, while VAWT + battery bridges evening and night demand. Hybrid microgrid models show that genetic algorithms or MILP can determine optimal numbers of PV modules/turbines and charge/discharge strategies to meet loads at minimum cost under local policy and tariff constraints (Merino & Castro, 2024). With reliable energy, DO-targeted control (rather than fixed schedules) becomes practical, as do variable-speed pump duties and graceful fallback modes during voltage dips. Consequently, ammonia/nitrite excursions can be prevented because aeration/recirculation continues through grid disturbances. Compact, higher-yield PV arrays enable expansion of grow beds without expanding the facility footprint, aligning with urban production needs. In short, high-efficiency PV embedded in a wind-supported hybrid microgrid strengthens technical readiness for continuous, energy-efficient, and resilient aquaponics.

Proof-of-concept deployments show that mobile dashboards can give operators instant visibility into DO and pH trends and remotely trigger actuators (pumps, blowers, dosing) through app-based controls integrated with the field devices (Khaoula et al., 2021). At larger scale, distributed aquaponics architectures link multiple sensor-actuator nodes over lightweight publish/subscribe protocols (e.g., MQTT) and a cloud gateway, which improves robustness via modular nodes, remote firmware updates, and clear fallback logic for critical loads such as aeration and recirculation (Alselek et al., 2022). With higher sampling rates,

robust signal processing (e.g., outlier filtering) and scheduled probe calibration reduce drift, while long-horizon logs establish baseline envelopes (e.g., safe pH ranges for nitrification) so subtle deviations are detected early. Beyond labor savings, continuous monitoring stabilizes weekly water-quality variance, lowers fish stress, and helps avert toxic excursions that periodic sampling often misses. These data streams also enable predictive control for example, model-predictive control (MPC) policies for DO that anticipate biological oxygen demand and coordinate aeration more efficiently, linking actions directly to quantifiable quality and cost indicators in daily operations (Chai et al., 2024).

The value of monitoring is realized when it drives early-warning and automatic mitigation. RAS-focused biosecurity assessments emphasize the need for dependable instrumentation, quarantine workflows, and rapid response to pathogen loads—lessons directly relevant to densely stocked aquaponics (Mota et al., 2022). With high-resolution DO/pH/ORP signals, systems can implement adaptive aeration (pre-emptively boosting blowers before DO crosses critical thresholds) and flow scheduling to avoid dead zones in media beds. Sensor fusion among pH, ammonia, and temperature supports estimation of unionized ammonia, more toxic than ionized forms to automate buffering or carbon dosing. Critically, this depends on energy availability for actuators. Hence, the PV-VAWT-battery stack reduces the risk of brownouts that can crash DO. Control policies can explicitly incorporate energy state (battery SOC and solar/wind forecasts) so aeration and recirculation are priority-one during scarcity, with noncritical horticulture lighting deferred. This tight integration of monitoring, control, and energy makes aquaponics self-correcting for common disturbances, closes decision-latency gaps inherent to manual operation, and keeps bioprocess performance within safe limits while providing auditable traces for continuous improvement (Merino & Castro, 2024; Mota et al., 2022).

To ensure consistent performance, we adopt SQCDM (Safety-Quality-Cost-Delivery-Morale) as a daily management framework that translates process signals into line-level action. Empirical evidence shows that digital SQCDP boards accelerate root-cause analysis and structured continuous improvement in both discrete and process industries (Ahmad Basri et al., 2024). In our platform, Q and C metrics are pulled directly from the sensor-energy data pipeline. Red/amber/green alarms trigger standard responses, and weekly retrospectives generate improvement experiments. Coupled with energy-aware operations from the hybrid microgrid, SQCDM binds technical (sensing, AI, energy) decisions to disciplined, auditable management practice (Ahmad Basri et al., 2024; Merino & Castro, 2024).

From an architectural perspective, recent surveys emphasize end-to-end pipelines that combine strong data augmentation, transfer learning, attention mechanisms, and explainable AI so models remain robust under variable lighting, camera angles, and occlusions common in dense grow beds. Reviews also underline the need for rigorous validation and domain-shift handling in field conditions (Duhan et al., 2024; Sarkar et al., 2023; Shoaib et al., 2023). Integrating vision outputs with dosing/actuation loops enables micro-nutrient adjustments and selective removal of diseased biomass to limit spread, while saliency tools such as Grad-CAM help operators verify that models focus on symptomatic tissues rather than backgrounds, improving trust and reducing overfitting (Karim et al., 2024). When coupled with environmental streams (canopy temperature/humidity) and water-quality metrics, learned models can forecast risk windows from historical patterns and trigger early interventions, which reduces pesticide use and improves harvest quality.

AI delivers greater value when it is tethered to water-quality signals and on-site energy availability. Disease-risk or stress alerts can be coordinated with lighting/ventilation to create microclimates unfavorable to pathogens, while pH/ORP set points are adjusted to keep biofilters within optimal regimes without stressing plants. Time-series models for aquaculture show that attention-based hybrids can predict dissolved oxygen dynamics from multi-sensor histories, enabling proactive control rather than reactive dosing (Karim et al., 2024). To keep costs down, training/inference is scheduled against the hybrid microgrid: heavier compute runs during PV surplus, while evening operations shift to low-power

modes, VAWT and batteries maintain critical loads. Contemporary microgrid studies provide sizing/dispatch methods to meet reliability targets at minimum LCOE, and tandem-PV roadmaps indicate rising module power density that benefits rooftop farms (Alberi et al., 2024; Merino & Castro, 2024). On the wind side, recent reviews catalog VAWT design strategies (e.g., variable-geometry, counter-rotation, diffuser or duct assistance) that raise power coefficient and suit turbulent built environments, which is attractive for aquaponics rooftops and courtyards (Didane et al., 2024; Lee et al., 2024). This architecture unifies camera streams, water sensors, and actuators under policies that balance Quality (plant/fish health), Cost (kWh, feed, spares), and Delivery (harvest reliability) with transparent, explainable recommendations to support operator action.

Feed dominates operating cost and is a major driver of water-quality variability. Precision-feeding research increasingly uses algorithms that fuse fish behavior, consumption rate, and DO dynamics to minimize uneaten feed and the ensuing ammonia spikes. Strategically, precision-aquaculture frameworks integrate sensors (cameras/acoustics/DO), analytics, and autonomous control to maximize growth while lowering emissions and input waste principles that translate well to aquaponics, where tank water quality is highly sensitive to feeding. Practical reviews of IoT in aquaculture document how these multi-sensor stacks are deployed and governed (Rastegari et al., 2023). Aligning feeding/aeration cycles with PV peaks helps maintain DO above thresholds and reduce ammonia transients across seasons, while clear HMIs expose daily feed/energy KPIs to sustain standardized responses and coaching.

The broader evidence base underscores both the urgency of low-emission, resource-efficient food systems and the technological readiness to deliver them. Recent FAO and IPCC reports quantify the dual pressure of food-security needs and climate constraints, strengthening the case for integrated, low-carbon production platforms [13,14]. Our contribution is a PV-VAWT-powered smart aquaponics architecture that combines continuous water-quality monitoring, energy-aware predictive control, computer-vision plant-health analytics, and SQCDM/SQCDP visual governance with traceable operational indicators. Scientifically, it synthesizes advances in high-efficiency PV (including the tandem roadmap), VAWT performance in complex urban flows, and microgrid optimization for cost-reliable supply. Engineering-wise, it translates sensor-edge-cloud stacks and precision feeding into measurable value, and managerially, it anchors Safety-Quality-Cost-Delivery-Morale in a digital daily cadence. Fieldable next steps include (i) closed-loop AI-energy-water with multi-objective MPC, (ii) low-profile VAWT trials on tropical rooftops, and (iii) an auditable SQCDP board for rapid replication across SMEs/community sites. Emerging studies on digital SQCDP implementations in lean settings show how such boards tie real-time metrics to problem-solving kata and standardized work, an approach we adapt to aquaponics operations. (Calvin et al., 2023; FAO et al., 2024).

This paper proposed the design of an aquaponic system with renewable energy applications by using wind turbines and solar panels, integrated with IoT and AI technology with FLC for automatic and precise data analysis, to ensure optimal system performance through the application of PSQCDM (Productivity, Safety, Quality, Cost, Delivery, Morale) principles (Schmidt & Schmidt, 2023). This system is capable of monitoring water quality parameters, such as temperature, pH, and Total Dissolved Solids (TDS) in real time. The use of renewable energy allows the system to operate independently, energy-efficiently, and in an environmentally friendly manner. The system's performance remains optimal even in areas with limited access to electricity. The purpose system increases the productivity and efficiency of urban farming, making a real contribution to the achievement of the Sustainable Development Goals (SDGs) in the areas of food security and clean energy. In this context, smart aquaponics powered by photovoltaics (PV) and vertical-axis wind turbines (VAWTs) offers a dual path: simultaneous fish-vegetable production via nutrient recirculation, real-time water-quality monitoring, and electrification of process loads through integrated renewables. Such integration can reduce micronutrient gaps, lower emissions intensity per kilogram of product, and increase operational resilience where the grid is unreliable. Because solar and wind profiles complement each other diurnally and

seasonally, hybridization stabilizes local supply without large footprints. Consequently, an aquaponics platform that is sensor-rich, energy-efficient, and governed with disciplined operational metrics is highly relevant to local food security strategies while contributing directly to SDG 2 (Zero Hunger) and SDG 7 (Affordable and Clean Energy) in Indonesia and other tropical regions.

2. Methods

2.1 Research design

This study employs a narrative literature review to develop a two-stage sorting concept for vending-point waste collection. Relevant studies were reviewed and synthesized to identify recurring patterns in sensing, control and AI, actuation, human-machine interfaces, and safety procedures. These findings were translated into a practical workflow and design parameters suitable for vending locations, considering input characteristics, space and power constraints, operator capabilities, and realistic throughput and accuracy targets.

2.2 Stage 1: Automated can detection and sorting

The first stage utilizes a Smart Automated Waste Management System (SAWMS) integrated with a Convolutional Neural Network (CNN)-based overhead camera positioned above a conveyor belt. The system detects aluminum cans in real time and coordinates a pick-and-place robotic arm equipped with a magnetic gripper. Design considerations include synchronization of the pick window with a belt encoder, CNN latency management, lighting optimization, region-of-interest tuning, and fallback operating modes to ensure reliable performance.

2.3 Stage 2: Plastic identification and classification

The second stage employs short-wave infrared (SWIR) hyperspectral imaging to identify plastic materials. Spectral data are processed through Principal Component Analysis (PCA) for dimensionality reduction and k-means clustering for material classification. The system is designed to exclude polyvinyl chloride (PVC) and acrylonitrile-butadiene-styrene (ABS) while directing polyethylene (PE), polypropylene (PP), and polystyrene (PS) streams toward pyrolysis processing. The workflow includes dark and white calibration, spectrum extraction, PCA transformation, clustering, quality-gate verification, and industrial controller-human-machine interface (HMI) integration.

2.4 Operational design and SCQDM evaluation

The technological concepts identified from the literature were translated into practical operational requirements for vending-point deployment, including infrastructure constraints, energy availability, operator competencies, throughput expectations, and classification accuracy targets. The resulting design was subsequently evaluated using the SCQDM framework, covering Safety, Cost, Quality, Delivery, and Morale dimensions to assess its feasibility, maintainability, and operational readiness.

3. Results and Discussion

3.1 Innovation of smart aquaponics System Based on IoT and renewable energy

The developed smart aquaponics system integrates Internet of Things (IoT) technology for automated water quality monitoring. The system is equipped with pH, temperature, Total Dissolved Solids (TDS), and Dissolved Oxygen (DO) sensors, ensuring optimal water quality for fish ecosystems and hydroponic plant nutrition. An artificial intelligence (AI)-

based camera employing the Mask R-CNN algorithm is applied for visual segmentation of hydroponic plants (e.g., lettuce). The primary function of this AI camera is to automatically detect plant health conditions and determine harvest readiness. Real-time monitoring data on water quality and plant status are transmitted to a Blynk-based application, enabling remote monitoring and sending notifications in cases of water anomalies, plant disorders, or harvest readiness.

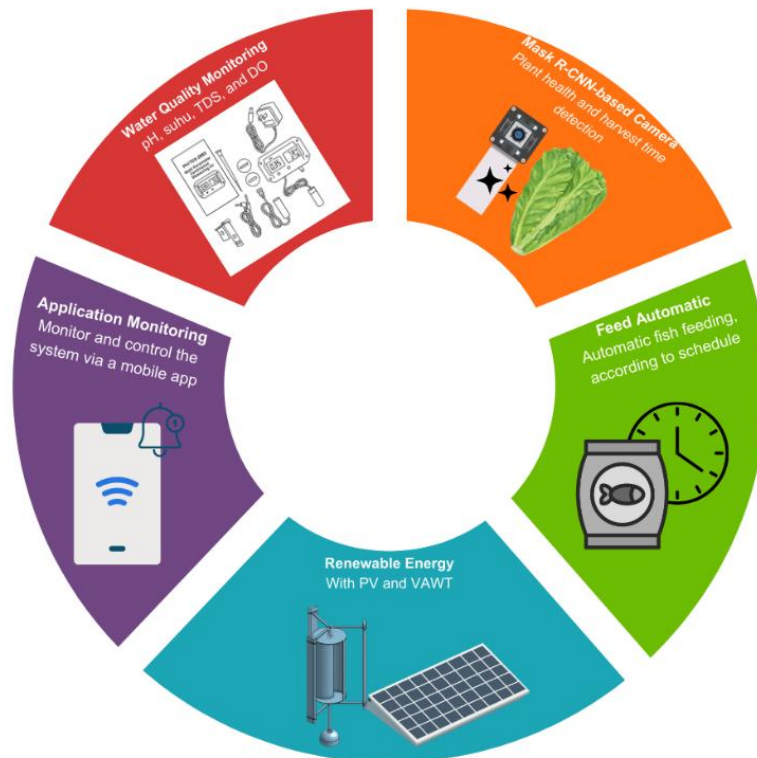


Fig. 1. Smart aquaponics system based on IoT, AI, and renewable energy

The system is also equipped with an automatic feeding feature that schedules fish feeding without requiring manual intervention. Power for the system is supplied by a hybrid combination of solar panels and a Savonius–Darrieus Vertical-axis Wind Turbine (HSDVAWT), ensuring uninterrupted energy availability throughout the day and night to meet significant water pump demands. This innovation provides an urban farming solution that combines precision technology with renewable energy. Its major advantages include efficient water quality monitoring, automated plant health detection, scheduled feeding, and environmentally friendly operation, making it a model for adaptive, efficient, and sustainable modern agriculture.

The system's operational cycle begins with IoT-based water quality monitoring that integrates temperature, pH, and TDS sensors. These sensors are installed within the aquaponics ecosystem to detect critical water parameters in real time. Sensor data are processed by a microcontroller using a Fuzzy Logic Controller (FLC) algorithm before being transmitted to a cloud-based monitoring application. The results are displayed through both a graphical user interface and the application, allowing users to monitor the water condition and receive alerts when parameters deviate from optimal values. This automated monitoring process stabilizes the aquatic and plant environment while reducing the risk of losses due to fluctuating water quality.

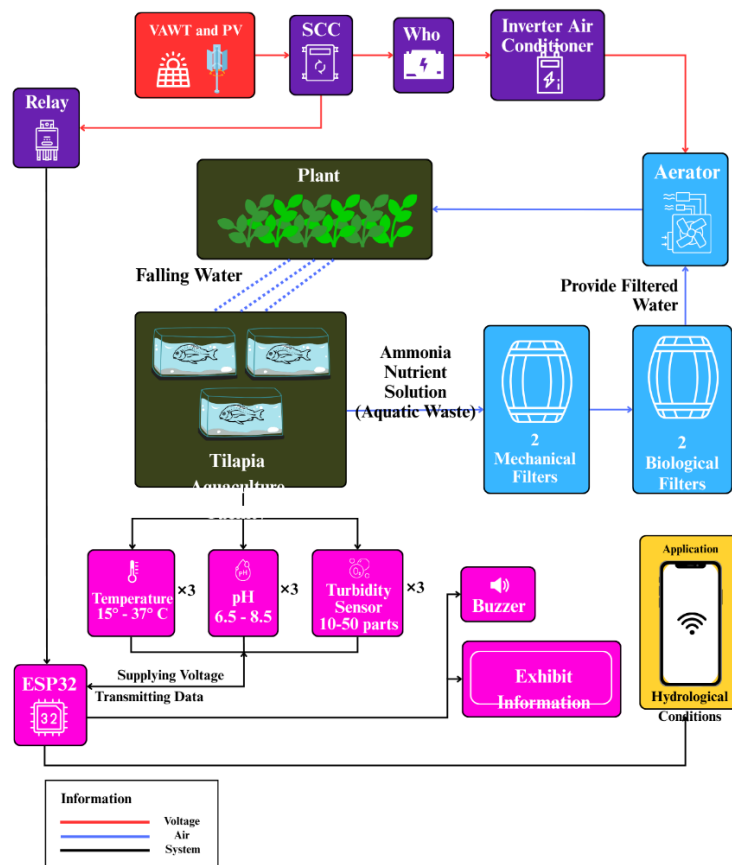


Fig. 2. Working principle of the proposed system

The automatic feeding system maintains a proper feed schedule according to fish growth requirements. Feeding is executed automatically based on pre-programmed schedules and feeding quantities, ensuring both precision and efficiency in nutrient management. This prevents overfeeding, which could increase ammonia levels and degrade water quality. Integrating water quality monitoring with the automatic feeding system demonstrably enhances productivity, sustains aquaponic operations, and facilitates efficient management.

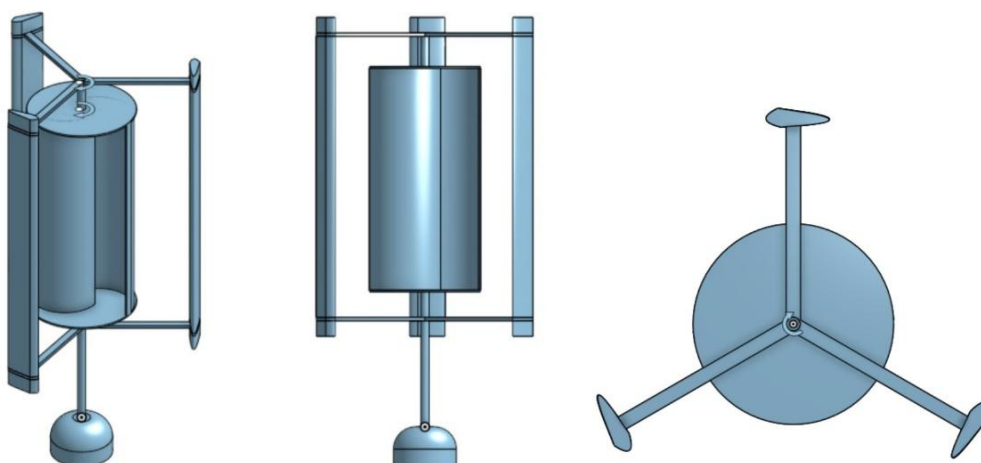


Fig. 3. Savonius-Darrieus Vertical-axis Wind Turbine

Based on the literature review, a hybrid vertical-axis wind turbine (VAWT), like Fig. 3, combining a lift-type Darrieus rotor with a drag-type Savonius rotor, is adopted to merge high starting torque with better mid-range efficiency, enabling self-starting at low wind speeds while sustaining output at higher tip-speed ratios (TSR). The Savonius rotor is

mounted coaxially inside the Darrieus, with a diameter ratio in the recommended 0.4–0.6 window (≈ 0.50 m vs 1.03 m $\rightarrow D_S/D_D \approx 0.49$) to reduce flow interference; the Darrieus height-to-diameter ratio is kept near 1.4 (1.45 m/1.03 m) for aerodynamic and structural stability. Darrieus blades use a symmetric profile (e.g., NACA 00xx) and a modest solidity ($c/D \approx 0.083$ from chord 0.0858 m) to limit cyclic loads, while the Savonius employs two semi-cylinders with thin end plates to curb tip leakage and boost starting torque. Slender support struts and adequate rotor clearances are used to cut parasitic drag and avoid premature stall. The 1:7 geometric scale preserves TSR similarity rather than Reynolds similarity, standard practice for small VAWTs, so start behavior, torque ripple, and power rise remain representative in laboratory tests. Operationally, the hybrid widens the useful range: the Savonius dominates below $TSR \lesssim 1$ for reliable self-start and gust tolerance, and the Darrieus takes over around $TSR 2\text{--}4$ for superior power capture well suited to turbulent, variable urban wind conditions.

Table 1. Estimated power consumption

Components	Real size (m)	Scale 1/7 (m)
Height of Darrieus blade	1.45	0.207
Diameter of Darrieus rotor	1.03	0.147
Chord length of the Darrieus blade	0.0858	0.0123
Height of the Savonius blade	1.00	0.143
Diameter of Savonius rotor	0.50	0.071
Thickness of the Savonius endplate	0.01	0.0014
Thickness of the Savonius blade	0.01	0.0014
Shaft diameter	0.014	0.002

3.2 SCQDM analysis of the smart aquaponics system

This section presents the main conclusions of the study. They should be presented in concise, clear, and compact sentences based on the results and discussions, in the form of paragraphs (not with bullet points or numbering), clarify the findings of the study as a synthesis of the results of the data analysis and discussion, and highlight original findings that contribute to the development of science. The main conclusion of the study may be presented in a short conclusions section, which may be stand-alone. It should not repeat the results, instead, it should provide significant findings and contributions of the study and the issue of this aim and scope of this journal.

3.2.1 Safety

This section presents the main conclusions of the study. They should be presented in concise, clear, and compact sentences based on the results and discussions, in the form of paragraphs (not with bullet points or numbering), clarify the findings of the study as a synthesis of the results of the data analysis and discussion, and highlight original findings that contribute to the development of science. The main conclusion of the study may be presented in a short conclusions section, which may be stand-alone. It should not repeat the results, instead, it should provide significant findings and contributions of the study and the issue of this aim and scope of this journal.

3.2.2 Cost

Based on the Budget Plan (RAB), the total implementation cost of the system is Indonesian Rupiah (IDR) 15,730,000. This includes main hardware (solar panels, wind turbine, pump, sensors, microcontroller, panel box, and batteries), assembly services, hosting, transportation, team consumption, documentation, publication, and user manual development. This investment is relatively competitive, as the system is fully integrated with IoT, renewable energy, and automation, offering substantial added value compared with conventional aquaponics systems.

Table 2. Estimated power consumption

Description	Value
Total Daily Hybrid Energy (PV dan VAWT)	1,700 Wh
Energy Consumption per system	1,320 Wh
Battery Energy Reserve	277 Wh
Backup Time (fully charged)	5 hours

The proposed system is designed to support sustainable and energy-efficient food production in urban environments. One system unit can operate continuously for 24 hours using a hybrid system consisting of a 100-watt-peak (WP) solar panel and a 150 W Vertical-Axis Wind Turbine (VAWT). The combination of solar and wind energy sources ensures a more stable power supply by compensating for fluctuations in weather conditions and sunlight availability. This hybrid configuration also reduces dependence on conventional electricity sources and contributes to lower operational costs and environmental impacts.

Table 3. Estimated revenue

Commodity	Quantity	Price/kg	Income (Rp)
Nile Tilapia	20 kg	30,000	600,000
Lettuce	16 kg	15,000	240,000
Total			840,000

The cost analysis shows that the hybrid system (solar panel and VAWT) eliminates monthly grid electricity expenses, limiting operational costs to fish feed, seedlings, and minimal maintenance. This reduction in energy-related expenditures significantly improves the economic feasibility of the system, particularly for small-scale urban farmers. Furthermore, the utilization of renewable energy sources enhances long-term sustainability by reducing dependence on conventional power supplies and minimizing carbon emissions associated with food production activities.

Table 4. Estimated investment cost and financial feasibility analysis

Description	Cost (Rp)
Initial Capital Investment (Equipment, Assembly, Services, etc.)	15,730,000
Operational Cost per Production Cycle (3 months)	546,000
Revenue per Production Cycle (3 months)	840,000
Net Profit per Production Cycle	294,000
Annual Net Profit (4 cycles)	1,176,000
Break-Even Point (BEP)	53.5 cycles (~13.4 years)

3.2.3 Quality

A Raspberry Pi 4 serves as the primary control unit, offering higher reliability, advanced data processing capability, and superior connectivity compared to conventional microcontrollers. The DS18B20 temperature sensor, PH-4502C pH sensor, and analog TDS sensor ensure accurate real-time water quality monitoring. A 100 WP solar panel and hybrid wind turbine guarantee a stable energy supply for pumps, sensors, and automated monitoring systems. The Raspberry Pi-based software allows for updates, analytics, and AI integration for visual detection, further improving productivity and sustainability.

3.2.4 Delivery

Key components such as Raspberry Pi 4, sensors, and renewable energy devices are widely available, minimizing procurement delays. Implementation follows a structured process that includes planning, equipment fabrication, system installation, user training, and final evaluation. Adequate budgeting for transportation and technician services facilitates field installation. The inclusion of user manuals and on-site training ensures timely system readiness.

3.2.5 Morale

The system was developed by a team with clear task allocation from design to training and publication. Budget allocation for training, documentation, and publication enhanced team motivation, professionalism, and competence in deploying the Raspberry Pi 4-based smart farming system. Engagement with beneficiary communities fostered collaboration and satisfaction, underlining the tangible impact of this innovation.

4. Conclusions

The developed smart aquaponics system demonstrates the integration of IoT-based sensing, AI-assisted monitoring, and hybrid renewable energy as an effective approach to enhance urban food production. Real-time tracking of water quality and automated feeding stabilize fish and plant ecosystems, while a hybrid photovoltaic-Darrieus-Savonius wind turbine provides a continuous, grid-independent power supply. The SQCDM analysis confirms that the system offers layered safeguards for safety, reliable sensor-actuator control for quality, transparent cost structures with renewable energy savings, standardized components for timely delivery, and user-centered dashboards and training for morale. Together, these features improve operational efficiency, productivity, and sustainability while reducing carbon emissions and resource consumption.

Future development should focus on scalability, adaptation to diverse local conditions, and integration of emerging technologies such as edge computing, blockchain for traceability, and more advanced AI-based automation. Cross-sector collaboration and enhanced digital education are essential to accelerate system adoption, improve technological literacy among urban farmers, and ensure inclusive solutions with broader impacts on the green economy and food security.

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Author Contribution

Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing – original draft preparation, writing – review & editing, visualization, supervision, and project administration: Y. L. S.. Design of Savonius–Darrieus vertical-axis wind turbine, specification development, and visualization: R. H. F.. SQCDM framework design, analysis, interpretation, and writing – review & editing: A. K. F..

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Declaration of Generative AI Use

During the preparation of this manuscript, the authors used generative artificial intelligence (AI) tools to assist with language editing and to create conceptual illustrations used in the manuscript. The authors carefully reviewed, revised, and validated all AI-assisted outputs to ensure their accuracy and appropriateness. No generative AI tools were used for data collection, data analysis, interpretation of results, or the generation of scientific conclusions. The authors take full responsibility for the content of this publication.

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