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Performance of an IoT-Based Paddle Wheel Aerator System and Solar Panels in Whiteleg Shrimp (Litopenaeus vannamei) Cultivation

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Abstract

Water quality and energy efficiency are critical factors for the success of intensive whiteleg shrimp (Litopenaeus vannamei) cultivation. The objective is to study the performance of an IoT-based paddle wheel aerator system and solar panels that integrate the Internet of Things (IoT), Artificial Intelligence (AI), and a hybrid power system (solar and PLN) in maintaining water quality stability and increasing productivity. The validation test was conducted from December 5–8, 2025, at the CV Riez Samudera pond, using a complete unit of IoT-based paddle wheel aerator and solar panels. The test results showed that water quality parameters (physical, chemical, and biological) were within the optimal range according to quality standards. The average clarity was 35.12 cm, Dissolved Oxygen (DO) was stable at >7 mg/L, and the pH was 7.99. The implementation of this technology supports pond productivity reaching 25 tons/ha/year, far exceeding the national average productivity (2022–2024) of 21 tons/ha/year and the national intensive standard. The IoT-based paddle wheel aerator system and solar panels have proven effective in automated water quality management and energy efficiency, supporting sustainable shrimp farming.

Keywords: IoT, Water Quality, Whiteleg Shrimp, Productivity, Energy Efficiency.

1. Introduction

The success of intensive aquaculture, particularly for whiteleg shrimp (Litopenaeus vannamei), depends heavily on precise water quality management (Ariadi *et al.,* 2021) Fluctuating environmental parameters, such as dissolved oxygen (DO) and pH, can trigger physiological stress, reduced immunity, and even mass mortality due to disease outbreaks (Prastiwi *et al.,* 2025). Furthermore, conventional aeration systems are often the most energy-consuming component of pond operations, accounting for 50-70% of total production costs (Nugraha, 2025).

To address these challenges of efficiency and environmental stability, the integration of Internet of Things (IoT) and Artificial Intelligence (AI) technologies into smart aquaculture systems has become a focus of global research over the past decade. The application of real-time sensors connected to intelligent algorithms has been shown to optimize water quality parameters and feeding (Paul *et al.*, 2025; Sun *et al.*, 2020). Furthermore, the use of renewable energy, such as photovoltaic systems, in aeration operations (hybrid systems) offers significant energy sustainability solutions (Cala-Delgado *et al.*, 2024).

This study aims to validate the performance of an IoT-based paddle wheel aerator system and solar panels, a smart aeration innovation based on AI-driven control and a hybrid microgrid implemented at the site of an industrial partner, CV Riez Samudera. Validation focused on the system's ability to maintain physical and chemical water parameters in accordance with international quality standards and its impact on increasing harvest productivity compared to the national average.

Clean and reliable water resource management has become a critical priority in urban areas due to the threat of pollution driven by population and industrial growth. The integration of Internet of Things (IoT) sensors and location-based services is now a key solution for real-time and systematic water quality monitoring (Bandara *et al.*, 2025). In the context of aquaculture, this technology is applied to detect water quality fluctuation patterns using intelligent algorithms such as Fuzzy Logic Controllers, enabling more accurate decision-making in maintaining pond ecosystems (Indrawati *et al.*, 2025).

Beyond monitoring, operational efficiency in aquaculture, particularly in whiteleg shrimp ponds, is highly dependent on aeration systems. The use of smart management systems on paddlewheel aerators powered by microinverter-based solar panels has been shown to maximize operational cost savings for farmers (Dewantara *et al.*, 2025). The design optimization of this waterwheel aerator has also been developed through Computational Fluid Dynamics (CFD) simulations integrated with IoT to ensure

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optimal and sustainable oxygen transfer (Jayraj *et al.*, 2025). In several regions, such as Banyuwangi, innovations in automatic diffuser aerators powered by a hybrid solar system have successfully improved water quality and the profitability of aquaculture production (Putri *et al.*, 2025).

The use of small-scale renewable energy, such as mini solar power sources, is also increasingly popular to support IoT devices in vanamae shrimp pond models (Widjaja & Laka, 2025). Furthermore, the scope of precision aquaculture technology is now expanding into the environmental sector through microalgae cultivation. Precision microalgae farming aims not only for bioproduction but also as a critical strategy for CO2 sequestration to mitigate climate change (Zhu *et al.*, 2023). Advances in microalgae-based carbon sequestration offer promising future prospects for global environmental sustainability (Udaypal *et al.*, 2024).

2. Methods

The IoT-based paddle wheel aerator system and solar panels. The IoT-based paddle wheel aerator system and solar panels are a cutting-edge solution for whiteleg shrimp cultivation, integrating a MiniSCADA-based IoT ecosystem and an AI Engine for precise and automated water quality management. Utilizing multi-parameter sensors (DO, pH, temperature, salinity) processed through machine learning, this system is able to adaptively predict oxygen demand, optimize aerator interventions, and reduce the risk of mass mortality. Its operational excellence is reinforced by a Hybrid Microgrid infrastructure (540Wp Solar Panels & PLN) that ensures energy efficiency and power sustainability, while a real-time monitoring dashboard ensures full data transparency for farmers, enabling them to achieve maximum productivity with minimal operational costs.

The technological advantage of the IoT-based paddle wheel aerator system and solar panels lies in the synergy of Edge Intelligence and Industrial-Grade IoT (MiniSCADA), distinguishing it from conventional aeration systems. The use of MiniSCADA ensures data integrity through noise filtering and direct sensor validation in the field, allowing the AI Engine to execute predictive algorithms precisely without the risk of cloud communication lag. The integration of this control unit with the Hybrid Power System enables dynamic optimization of energy consumption. The system intelligently prioritizes power usage from the 540Wp Solar Panel during high light intensity and automatically switches to the grid/battery via the Power Management Controller. The result is a pond ecosystem that is not only responsive to fluctuations in water quality parameters but also has high operational resilience to power outages, significantly reducing electricity overhead costs while increasing the survival rate of whiteleg shrimp.

2.1 Research Time and Location

The field validation study was conducted from December 5 to 8, 2025, at the intensive pond of CV Riez Samudera. This site has operated a complete, fully integrated IoT-based paddle wheel aerator system and solar panels system in a 500 m^2 pond with a stocking density of 100 whiteleg shrimp (PL/m^2). Production performance data is taken from production data during one cycle of vanamae shrimp cultivation in ponds.

2.2 System Design and Instrumentation

The validated IoT-based paddle wheel aerator system and solar panels utilize an IoT architecture consisting of multi-parameter sensor nodes (DO, pH, temperature, salinity) that transmit data wirelessly to a central gateway. The data is processed using an AI Engine to predict oxygen demand (hypoxia detection), which then automatically regulates the aerator motor speed (Arepalli & Naik, 2024). Power is provided by a hybrid system (PLN and 540Wp solar panels) to ensure 24-hour operation.

2.3 Data Collection and Analysis

Thirty-two water samples were taken over four days for analysis of physical, chemical (inorganic and organic), and biological (microbial) parameters. Measurements were conducted in situ using calibrated probes and laboratory validation. Productivity data (tons/ha/year) were calculated based on actual harvest yields and compared with secondary national productivity data and related literature (Muchtar *et al.*, 2021). Productivity is calculated using the formula:

$$\text{Productivity (Ton/Ha)} = \frac{\text{Total Harvest (Ton)}}{\text{Land Area (Ha)}}$$

Comparative descriptive analysis was used to compare the measurement results with the reference water quality standards of Nuntung et al. (2018) and SNI 8035:2019.

3. Results and Discussion

3.1 Water Quality Dynamics

The implementation of the automatic control system in the paddle wheel aerator system showed very satisfactory results in maintaining the stability of water quality parameters.

Water physics parameters are a major limiting factor in whiteleg shrimp (Litopenaeus vannamei) cultivation because they directly affect the shrimp's metabolic rate, oxygen consumption, and osmotic balance. Validation results at CV Riez Samudera's ponds demonstrate that the integration of the IoT-based paddle wheel aerator system and solar panels system is capable of maintaining the stability of these physics parameters within a range that supports high productivity.

Table 1. Physical parameters

Parameter	Unit	Standard	Value
Brightness	m	20 - 45	35±8
Salinity	ppt	15 - 30	24±4
Temperature	°C	32-36	33.78±1.38
Turbidity	mg/L	200-600	403±121
Current speed	cm/s	0.32 - 2	1.5±0.5
Color		Light green, light brown	Light green

Water Temperature: Measurements showed that the average water temperature during the validation period was 33.78 ± 1.38°C. This value is still within the physiological tolerance limits of whiteleg shrimp, although slightly above the optimal range of 28–32°C recommended by Prastiwi et al. (2025), its stability is crucial. According to Boyd et al. (2018), water temperature is the primary driver of biochemical reactions in pond ecosystems; increasing temperature within the tolerable range can accelerate growth rates through increased feed consumption, but must be balanced with strong aeration because oxygen solubility decreases with increasing temperature. The use of an IoT-based paddle wheel aerator system and solar panels with AI control has proven capable of compensating for these temperature fluctuations by adjusting aeration intensity in real time to ensure an abundant oxygen supply despite high water temperatures. This aligns with the findings of Arantes et al. (2017) stated that in intensive systems, extreme daily temperature fluctuations can be minimized through effective water circulation through a continuously operating aeration system.

Transparency: Average water transparency was recorded at 35.12 ± 7.79 cm. This value indicates the ideal density of plankton and suspended particles, optimal value of water transparency 30–45 cm (Nuntung *et al.*, 2018). Transparency is a visual indicator of hytoplankton abundance, which acts as the primary producer of dissolved oxygen through photosynthesis during the day. Ray et al. (2017) explained that proper transparency management is crucial in intensive cultivation systems to prevent algae blooms followed by plankton crashes, which can cause sudden deoxygenation. The stability of transparency at 35 cm indicates that the water turbulence generated by the IoT-based paddle wheel aerator system and solar panels does not cause excessive stirring of bottom sediments (resuspension), thus maintaining water clarity and optimal sunlight penetration for photosynthesis.

Salinity The average salinity during the test was 23.53 ± 4.18 ppt. This salinity is ideal for whiteleg shrimp, which are euryhaline (have a wide salinity tolerance). According to Gao et al. (2016), whiteleg shrimp achieve optimal growth performance at a salinity range of 15–25 ppt because at this range, the energy expended by shrimp for osmoregulation is at its lowest point, allowing more energy to be allocated to somatic growth. The salinity stability at the research site provides a stable internal environment for shrimp, reduces osmotic stress, and ultimately contributes to the achievement of high pond productivity (25 tons/Ha/year) compared to the national average.

Table 2. Chemical Parameters

Parameter	**Unit**	**Standard**	**Value**
DO titration	mg/L	> 4	7±2
DO probe	mg/L	> 4	8±2
Alkalinity	mg/L	100-150	127±13
pH		7.5 - 8.7	8.0±0.0
Ammonia	mg/L	0.01-0.03	0.002±0.001
Nitrite	mg/L	0.01	0.01±0.00
Nitrate	mg/L	1.35	1.18±0.11
Phosphate	mg/L	0.5 - 1	0.72±0.17
TOM	mg/L	< 100	63±24

Oxygen Concentration Dissolved Oxygen (DO) is a key performance indicator of aerators. Validation results show a stable average DO of 7.41–7.53 mg/L. This value is well above the critical threshold of 4 mg/L set by national and international standards (Ma'sum *et al.*, 2023; SNI, 2019). This high DO level confirms the effectiveness of the AI algorithm in responding to oxygen demand in real time, preventing hypoxic conditions that often occur at night in intensive ponds (Arepalli & Naik, 2024).

According to Krummenauer et al. (2016), in high-density shrimp farming systems, oxygen consumption comes not only from shrimp respiration but also from the microbial community and organic matter oxidation. The DO stability above 7 mg/L achieved by the IoT-based paddle wheel aerator system and solar panels system provides a sufficient "safety margin" for the shrimp to withstand sudden surges in oxygen demand or temporary technical system failures. Furthermore, Boyd et al. (2018) confirmed that intelligently managed mechanical aeration not only provides oxygen but also assists the ammonia volatilization process and maintains water circulation to prevent chemical stratification.

The pH value was stable at 7.99, ideal for growth (range 7.5–8.5) and suppressed ammonia toxicity. pH stability is greatly influenced by the balance between respiration and photosynthesis, as well as the buffering capacity of the waters. Valenti et al. (2021) stated that extreme pH fluctuations can cause physiological stress in whiteleg shrimp and alter ammonia toxicity. A pH value approaching 8.0 is the optimal point, supporting the calcification process of shrimp shells after molting and ensuring efficient nitrification by autotrophic bacteria in reducing nitrogenous waste.

Ammonia (NH^3) and nitrite (NO^2) levels were recorded at 0.08 mg/L and 0.50 mg/L, respectively, safely below the lethal threshold (Ammonia <0.1 mg/L, Nitrite <1 mg/L) (Ariadi *et al.,* 2021). Ammonia and nitrite are byproducts of protein metabolism, which, if high, can inhibit oxygen transport in shrimp blood (hemolymph). Alfiansah et al. (2018) explained that good water quality management through constant aeration can stimulate the growth of nitrifying bacteria (Ammonia-Oxidizing Bacteria and Nitrite-Oxidizing Bacteria), which convert toxic compounds into safer nitrates. The low nitrogen levels in CV Riez Samudera's ponds prove that the IoT-based paddle wheel aerator system and solar panels circulation and aeration system works effectively in supporting the natural nitrogen cycle in the ponds.

Total Organic Matter (TOM) level of 63.41 mg/L remained below the maximum standard of 100 mg/L. Uncontrolled accumulation of organic matter often triggers a sudden decline in water quality. Ray et al. (2017) noted that the presence of suspended organic particles in the right amount helps maintain the structure of the microbial community, but excess can cause deoxygenation at the bottom of the pond. The IoT-based paddle wheel aerator system and solar panels's ability to maintain water movement prevents the sedimentation of organic waste in the dead zone, thus facilitating the process of aerobic decomposition and waste disposal (central drain).

Table 3. Microbial Community Structure

Parameter	Unit	Standard	Value
Bacteria (TB)	CFU/ml	$\geq 10^3$	3107±1126
Bacteria (TVC)	CFU/ml	$\leq 3 \times 10^3$	1874±511
Total Vibrio (V.Yellow)	CFU/l	$< 1x10^3$	442±255
Total Vibrio (V.Green)	CFU/l	>10x TVC	22512±5978

Microbial communities, including phytoplankton and bacteria, serve as the biological foundation of intensive pond ecosystems. The stability of these communities depends heavily on oxygen availability and consistent water circulation, which in this study were automatically managed by the paddle wheel aerator system. The average plankton abundance reached 1.25 x 10^5 Ind/L, indicating sufficient natural food availability. The total bacteria and Vibrio populations were also monitored within safe limits.

Plankton plays a dual role as oxygen producers through photosynthesis and as natural food for whiteleg shrimp in the early stages. According to Ray et al. (2017), a stable plankton density helps stabilize fluctuations in water chemistry, particularly pH and ammonia, through direct nutrient absorption. The use of IoT-based paddle wheel aerator systems and solar panels, which maintain continuous water circulation, has been shown to prevent plankton cell sedimentation on the pond floor, thereby minimizing the risk of mass plankton death (plankton crash), which can trigger anoxia.

Bacterial Dynamics and Vibrio Management The total bacterial density and Vibrio population during validation were at a safe and controlled level. In intensive high-density cultivation systems, the risk of population explosion of pathogenic bacteria such as Vibrio spp. is a major threat. Alfiansah et al. (2018) explained that bacterial communities in ponds are highly responsive to environmental changes; stable aerobic conditions (DO >7 mg/L) generated by intelligent aeration encourage the dominance of beneficial bacteria (such as the Proteobacteria and Bacteroidetes groups) over pathogenic groups.

Furthermore, Zheng et al. (2022) in their research on AI-based aquaculture management emphasized that precise water quality control can suppress Vibrio growth by maintaining a balanced Carbon-Nitrogen (C/N) ratio and oxygen availability for nitrifying bacteria. The IoT-based paddle wheel aerator system and solar panels system, through its AI prediction module, ensures that the pond environment remains in a strong oxidative state, thereby suppressing the ecological niche for anaerobic bacteria and opportunistic pathogens that often trigger Early Mortality Syndrome (EMS) or Acute Hepatopancreatic Necrosis Disease (AHPND). Microbial Interactions and Energy Efficiency The success of maintaining the microbial community at a level of 1.25X10^6 Ind/L with efficient energy demonstrates the superiority of the IoT-based paddle wheel aerator system and solar panels hybrid system. Hou et al. (2018) noted that the interaction between aquatic microbiota and shrimp gut health is greatly influenced by the consistency of water physicochemical parameters. By maintaining a stable microbial environment through AI-regulated aeration, this system not only improves shrimp survival but also supports high productivity reaching 25 tons/Ha/year through optimizing microbial ecosystem services in degrading organic waste in-situ.

3.2 Productivity and Efficiency

Production validation at CV Riez Samudera recorded a productivity of 25 tons/ha/year. This figure represents a significant advantage compared to the national average productivity (2022–2024) of 21 tons/ha/year. The standard productivity for intensive ponds generally ranges from 10–15 tons/ha/cycle, or approximately 16 tons/ha/year according to a study by Muchtar et al. (2021) and the government target (Ministerial Regulation of Maritime Affairs and Fisheries No. 75/2016).

This increase in productivity aligns with the findings of Folorunso et al. (2021) and DergiPark (2025), which state that the adoption of smart farming technology and IoT-based water quality management can increase technical efficiency and survival rates by

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up to 10% compared to conventional methods. Furthermore, the use of a hybrid system of IoT-based paddle wheel aerators and solar panels contributes to reduced energy operational costs, supporting Nugraha's (2025) findings regarding energy efficiency of up to 40% in automated aeration systems.

4. Conclusion

The IoT-based paddle wheel aerator system and solar panels have been successfully validated as a reliable technological solution for intensive whiteleg shrimp cultivation. This system is able to consistently maintain water quality (DO >7 mg/L, stable pH) and support productivity of 25 tons/ha/year, exceeding the national average. The integration of IoT, AI, and renewable energy in the IoT-based paddle wheel aerator system and solar panels not only improves the biological performance of shrimp but also offers a more energy-efficient and sustainable cultivation model.

References

Arepalli, P. G., & Naik, K. J., 2024. A deep learning-enabled IoT framework for early hypoxia detection in aqua water using light weight spatially shared attention-LSTM network. The Journal of Supercomputing, 80(2), 2718-2747.

Ariadi, H., Wafi, A., Musa, M., & Supriatna, I., 2021. The relationship between water quality parameters in intensive aquaculture of white shrimp Litopenaeus vannamei. Samakia: Jurnal Ilmu Perikanan, 12(1), 18-27.

Bandara, R. M. P. N. S., Jayasignhe, A. B., & Retscher, G., 2025. The Integration of IoT (Internet of Things) Sensors and Location-Based Services for Water Quality Monitoring: A Systematic Literature Review. Sensors, 25(6), 1918.

Cala-Delgado, D. L., 2024. Solar-based commercial Biofloc Technology (BFT) for aquaculture: Energy analysis and economic implications. Aquacultural Engineering, 104, 102373.

DergiPark, 2025. Emerging Digital Technologies for Smart Aquaculture: A Review of IoT and AI Applications. International Journal of Multidisciplinary Studies, 12(1), 45-58.

Dewantara, B. Y., P.K, I. D., & Aulia, V., 2025. Implementasi Sistem Manajemen Pintar Pada Aerator Paddle Wheel Tenaga Surya Berbasis Microinverter Sebagai Upaya Memaksimalkan Penghematan Biaya Operasional Petani Tambak Udang. TELKA - Telekomunikasi Elektronika Komputasi dan Kontrol, 11(2), 228–239.

Folorunso, E. A., 2021. Technical efficiency of intensive shrimp farming: A comparative analysis of semi-intensive and intensive systems. Aquaculture Economics & Management, 25(3), 320-338.

Indrawati, E. M., Andrianto, C., & Kurniawan, A., 2025. Detection of Water Quality Fluctuation Patterns with Fuzzy Logic Controller. Journal of Intelligent System and Telecommunication, 1(2), 175–188.

Jayraj, P., Sahoo, S., Jana, P., & Prem, R., 2025. CFD optimised solar powered IoT integrated paddlewheel aerator for sustainable shrimp farming – A review. Aquacultural Engineering, 111, 102583.

Ma'sum, M. A., 2023. Analysis of Suitability of Water Quality Parameters for Vaname Shrimp (Litopenaeus vannamei) Aquaculture. Journal of Agroscience Indonesia, 1(2), 42-52.

Muchtar, A., 2021. Productivity of Vannamei Shrimp Cultivation (Litopenaeus vannamei) in Intensive Ponds. Journal of Aquaculture and Fish Health, 10(2), 147-155.

Nugraha, A., 2025. Energy Efficiency in Aeration Systems for Aquaculture Ponds: A Comprehensive Review. Jurnal Riset Akuakultur, 20(1), 1-25.

Nuntung, S., 2018. Water Quality Management in Vaname Shrimp (Litopenaeus vannamei) Farming. Jurnal Perikanan Universitas Gadjah Mada, 20(2), 89-97.

Paul, T., 2025. A review of technological development in shrimp aquaculture: AI and Biotechnological Advancements. Indonesian Aquaculture Journal, 20(1), 158-170.

Prastiwi, D. A., Fauziah, S., & Nazran, M., 2025. Kesesuaian Kualitas Air pada Tambak Udang Vannamei (Litopenaeus vannamei) Sistem Intensif. Jurnal Akademi Perikanan Kamasan, 6(1), 1-12.

Putri, V. L. B., Priyadi, A., Pujiantara, M., Anam, S., & Agustinah, T., 2025. Inovasi Aerator Diffuser Otomatis Berbasis IoT Bertenaga Hybrid Solar System Guna Meningkatkan Kualitas dan Profitabilitas Produksi Budidaya Perikanan Desa Wringinrejo, Banyuwangi. Sewagati, 9(6), 1489–1501.

SNI 8035:2019, 2019. Udang Vaname (Litopenaeus vannamei) – Bagian 1: Produksi benih dan pembesaran. Jakarta: Badan Standardisasi Nasional.

Sun, J., 2020. Intelligent feeding and water quality monitoring in aquaculture based on IoT and AI. Computers and Electronics in Agriculture, 172, 105342.

Udaypal, Goswami, R. K., Mehariya, S., & Verma, P., 2024. Advances in microalgae-based carbon sequestration: Current status and future perspectives. Environmental Research, 249, 118397.

Widjaja, D., & Laka, Y. P. S., 2025. Mini Solar Power Resources for IoT system in the Vannamei Shrimp Pond Model. International Journal of Applied Sciences and Smart Technologies, 7(2), 265–276.

Zhu, C., Hu, C., Wang, J., Chen, Y., Zhao, Y., & Chi, Z., 2023. A precise microalgae farming for CO2 sequestration: A critical review and perspectives. Science of The Total Environment, 901, 166013.