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Precision Ulang Aquaculture: A Sustainable Approach Leveraging Atmega2560-based Automation and Data-Driven Control

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Abstract. Freshwater prawn (*Macrobrachium rosenbergii*, locally known as *Ulang*) aquaculture is a significant livelihood in the Philippines, but is often constrained by traditional methods leading to resource inefficiency and variable yields. This study addresses the need for enhanced operational efficiency and environmental stability in traditional Ulang farming by designing and quantitatively evaluating a novel, ATmega2560-based automated control system for data-driven water quality management. The ATmega2560-controlled system integrates sensors for continuous real-time monitoring of six critical water parameters (Temperature, pH, DO, Salinity, Ammonia, and Water Level). It uses actuators (pumps and coolers) to automate precise water-quality regulation. Sensor accuracy was rigorously validated over five trials against reference devices, yielding an Overall Average Accuracy of 96.66% across all parameters, confirming an 'Excellent' performance rating. Furthermore, the system maintained a 0% disease rate and achieved an 85.33% cumulative survival rate over a three-month grow-out period, which is substantially higher than reported low-survival ranges. These results establish the feasibility and reliability of accessible microcontroller technology for efficient, data-informed ulang farming, offering a scalable solution to mitigate environmental stress, improve prawn survival, and optimize operational resource use.

Keywords*: Precision aquaculture, sustainable approach, Ulang, ATmega2560, automation, data-driven control*

Introduction

Macrobrachium rosenbergii, the giant freshwater prawn or 'ulang' as it's known locally in the Philippines, is a crustacean of significant economic and nutritional value across the Indo-Pacific (Tan & Wang, 2022). Its natural distribution spans from northwest India through Southeast Asia to northern Australia (Brown, 2022).

With desirable characteristics including fast growth, the potential to reach three prawns per kilogram, and a flavor profile comparable to lobster (Wiguno & Dewi, 2022; Hooper et al., 2022), M. rosenbergii represents a key opportunity for Philippine aquaculture. However, achieving consistent success and predictability in its cultivation is hindered by significant obstacles.

A primary challenge is achieving high, consistent survival rates throughout the culture period. Reports indicate that survival can be problematically low, sometimes ranging from 12% to 37% under certain conditions (Wiguno & Dewi, 2022; Juneta-Nor et al., 2020). Factors contributing to mortality include broodstock quality, cannibalism, disease (Juneta-Nor et al., 2020), and crucially, deviations from optimal water quality (Clark, 2016; Juneta-Nor et al., 2020). Pathogens like White Spot Syndrome Virus (WSSV) represent a serious threat, capable of causing up to 100% mortality within just 3-10 days in infected ponds (Clark, 2016; Kumar et al., 2020; Hooper et al., 2022). Ensuring optimal environmental conditions is paramount for mitigating stress and supporting prawn health. Key water quality parameters include temperature, pH, dissolved oxygen, low ammonia levels, and suitable salinity levels (Bir et al., 2024).

Maintaining these parameters within optimal ranges using traditional methods can be labor-intensive and prone to inconsistency. Addressing this gap, intelligent aquaculture approaches offer a promising avenue for leveraging the Internet of Things (IoT), enabling continuous environmental monitoring through various sensors (e.g., for temperature, pH, DO, ammonia, water level) (Suhaili et al., 2023; Satra et al., 2024; Hairol et al., 2018). By processing this real-time data, automated systems can trigger control actions, such as adjusting aeration or managing water exchange (Ahmed & Turchini, 2021), ensuring conditions remain stable and suitable for prawn growth and survival. This data-driven precision farming aims to enhance efficiency, reduce risks associated with human error and environmental fluctuations, optimize resource use, and ultimately improve the viability and productivity of M. rosenbergii farming. Controlled prawn feeding may save costs and benefit the environment without hindering growth or nutrition (Rahman et al., 2020).

Based on the identified literature gap, this study poses the primary hypothesis: An ATmega2560-based automated control system that provides high-accuracy water quality management will significantly improve ulang survival rates and operational consistency compared to traditional manual methods.

This project addresses the challenge of achieving consistent success in Ulang cultivation by focusing on the design, implementation, and quantitative evaluation of an ATmega2560-based automated control system. The novelty of this prototype lies in its accessible, low-cost microcontroller technology combined with comprehensive, six-parameter data-driven control, specifically tailored for resource-efficient precision aquaculture in a Philippine context. The study's primary objective is to evaluate the system's accuracy and operational reliability in maintaining optimal water quality and its subsequent impact on key performance metrics like disease and survival rates during the grow-out phase.

Methodology

The Prototyping Model used in this study is shown in Figure 1. This methodology was effective in obtaining the study's objectives. It involves the process of gathering inputs and requirements, designing concepts, an actual prototype, prototype evaluation, and if the prototype passes, then implementation to model setting and maintenance is the last step to achieve an effective result.

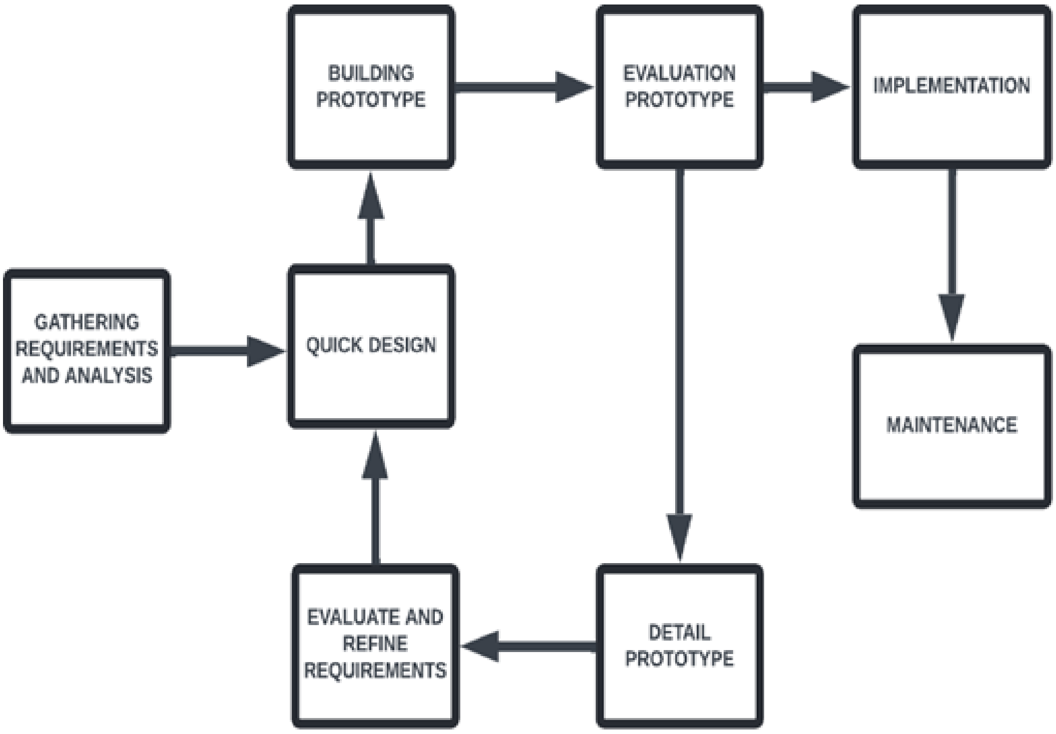

Figure 1: Prototyping Model

The conceptual framework, including the Input, Process, and Output, is shown in Figure 2. The system requires an AC power source to operate, which is converted to regulated DC power to supply the control unit. The primary focus of the study is to test the system using freshwater, specifically targeting the grow-out phase for Ulang aquaculture. The testing environment used a pond measuring 5 meters × 5 meters, with a structural height of 3 feet and a maintained water level of 2.2 feet (0.67 meters), resulting in a total operating volume of approximately 16.75 m3. The process involves several steps, which describe how the various sensors monitor key water parameters, including temperature, pH, water level, dissolved oxygen, salinity, and ammonia content. The actuators used to maintain water parameters are interconnected via an ATmega2560 microcontroller. The microcontroller processes sensor data and activates actuators to maintain optimal conditions for Ulang's growth and health.

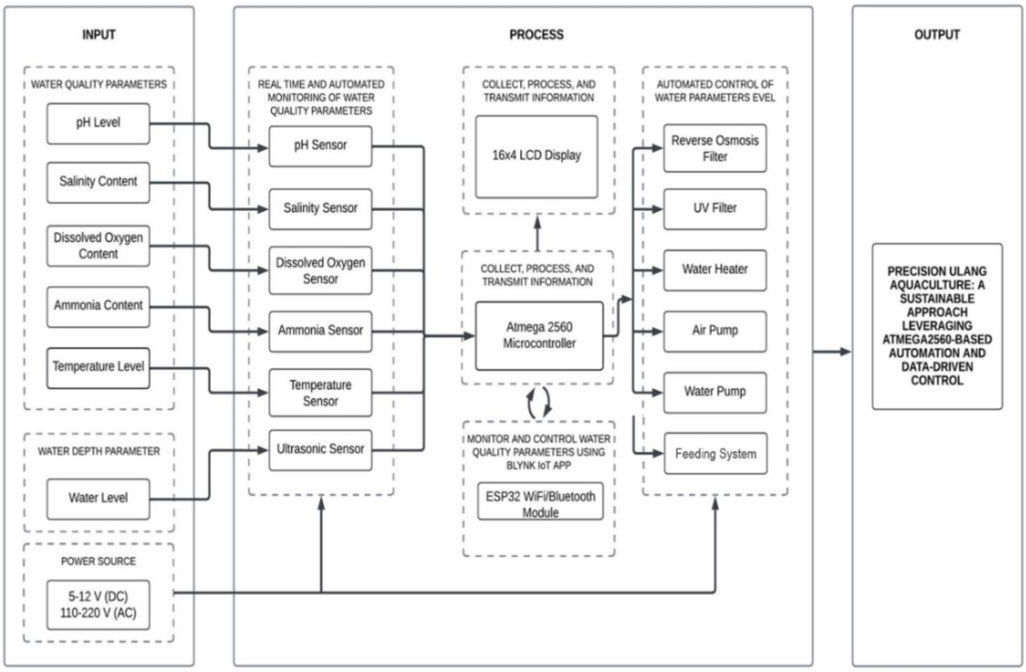

Figure 2: Conceptual Framework

The system's sensors were calibrated and validated using commercial, lab-grade reference equipment to establish the ‘True Value’ for accuracy assessment. For instance, pH and Temperature readings were cross-verified using a calibrated handheld multimeter (Hanna Instruments HI98194 Multi-Parameter Meter). Calibration for all six parameters involved two steps: first, adjusting sensor output against the reference device in a control environment; and second, conducting five separate trials across three operational conditions (Below Optimal, Optimal, and Above Optimal) to assess consistency and error.

Component Type	Component Name	Key Specification	Operational Range / Unit	Function in System
Microcontroller	Arduino Mega 2560	ATmega2560 (16 MHz)	54 Digital I/O pins	Central processing and control unit
Sensor (Temp)	DS18B20	Digital, Waterproof	−55∘C to 125∘C	Measures water temperature
Sensor (pH)	pH-4502C	Analog	0 to 14 pH	Measures acidity/alkalinity of water
Sensor (DO)	Dissolved Oxygen Sensor	Galvanic/ Polarographic	0 to 20 mg/L	Measures oxygen concentration
Sensor (Ammonia)	MQ-135 Gas Sensor	Analog Output	10 to 1000 ppm	Monitors water contamination/ammonia
Sensor (Salinity)	Conductivity Sensor	Analog, K=10	0 to 10 ppt	Measures salinity/conductivity
Sensor (Level)	Ultrasonic Sensor HC-SR04	Non-contact	2 cm to 400 cm	Measures water depth for level control
Actuator	Air Pump AP-808	12V/3A	Aeration control	Increases dissolved oxygen levels
Actuator	Submersible Pump XZ-1200	12V/5A	Water exchange control	Replenishes or circulates water
Actuator	Thermoelectric Cooler TEC-12706	12V/10A	Temperature control	Lowers water temperature

Figure 3: Reference Devices and Calibration Procedure

The evaluation of the prototype was conducted over three months within a controlled pilot farm environment to ensure that the results were representative of real-world operational challenges while maintaining data integrity. Replicability is further enhanced by providing the detailed circuit schematic of the ATmega2560 control system in Figure 4.

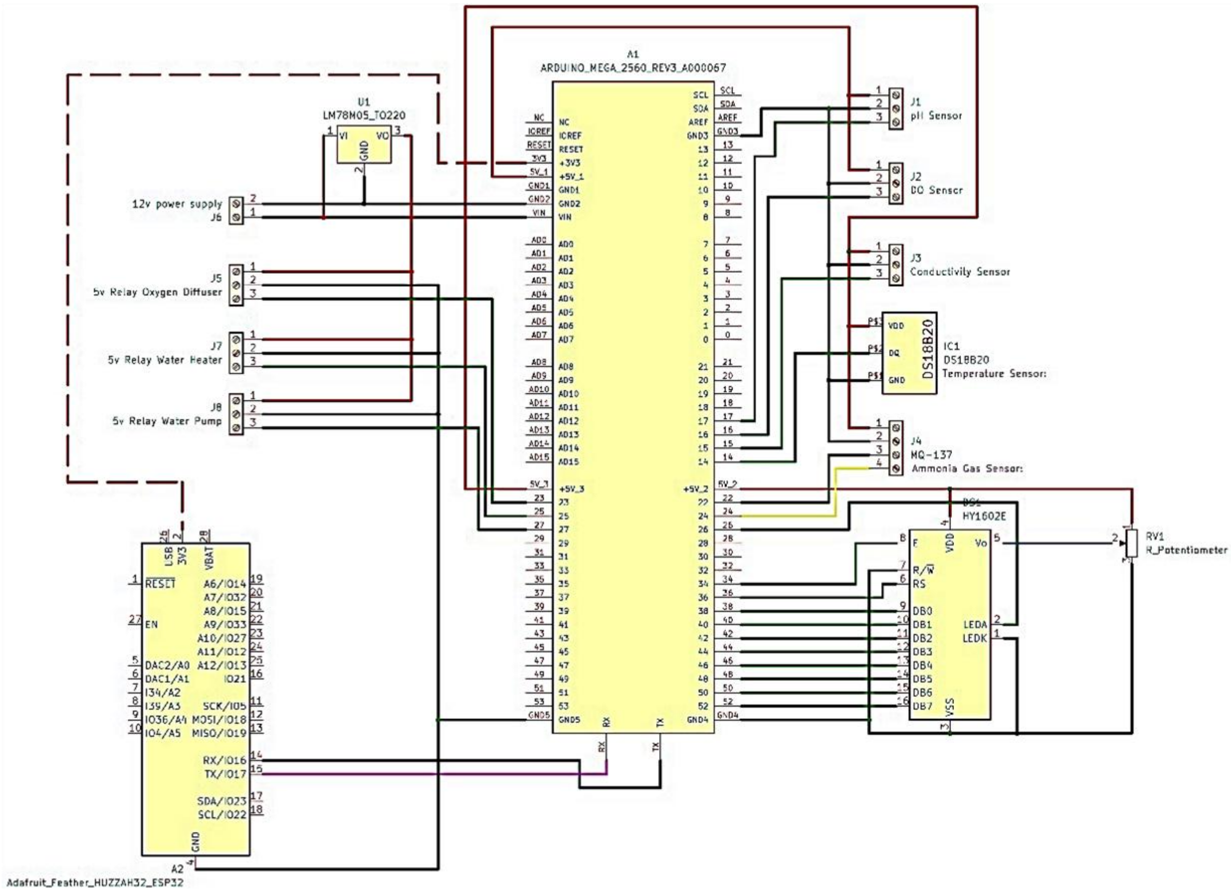

Figure 4: Schematic Diagram of the ATmega2560 Control System

Results

A. Functionality Test

Table 1 presents the overall functionality results for all listed major hardware components, including the control unit (Arduino Mega) and actuators (pumps, cooler, relays), as well as the power supply, display, and communication module, which were tested against their required functions and performed correctly according to the test plan. This confirms the basic operational integrity of the system's individual hardware elements. The evaluation used a four-tier performance scale: Poor, Good, Satisfactory, and Very Satisfactory. The key finding from this table is that all sensors evaluated performed exceptionally well, achieving the highest possible rating of "Very Satisfactory." Furthermore, the “PASSED” remark for each sensor indicates that it successfully met the predefined criteria and operational requirements set during the functionality testing phase.

COMPONENT DETAILS	NO. OF FUNCTIONAL REQUIREMENTS	TEST STEP	REMARKS
Arduino Mega 2560 (12V/1A)	5	5	PASSED
Submersible Pump XZ-1200 (12V/5A)	7	7	PASSED
Air Pump AP-808 (12V/3A)	7	7	PASSED
Thermoelectric Cooler TEC-12706 (12V/10A)	6	6	PASSED
12V Relay Module 8-Channel (12V/2A)	5	5	PASSED
12V/20A Switching PSU (220V AC Input)	3	3	PASSED
16x2 LCD Display (5V/0.5A)	4	4	PASSED
ESP32 WiFi/Bluetooth Module (5V/1A)	5	5	PASSED

Table 1: Overall Result for Sensor’s Functionality

B. Accuracy Test

The system’s accuracy was evaluated during trials by calculating the percentage error in sensor readings of freshwater parameters at the grow-out level in the *Ulang* aquaculture. The proponent used 5 trials to assess the system's accuracy. Table 2 shows the method used to determine the Likert scale category for water quality parameters.

$$\text{Percentage Error} = \left| \frac{\text{Measured Value} - \text{True Value}}{\text{True Value}} \right| \times 100\%$$

Numerical Percentage (%) Range for Accuracy Value	Verbal Interpretation
96 – 100	EXCELLENT
91 – 95	VERY SATISFACTORY
86 – 90	SATISFACTORY
81 – 85	VERY GOOD
76 – 80	GOOD

Table 2: Degree of Percent Accuracy

Beyond the percentage accuracy, the reliability of the prototype was statistically assessed. The consistently low Mean Absolute Error (MAE) across all sensor types indicates that the system's readings are consistently close to the laboratory-grade ‘True Value.’ Furthermore, the low Standard Deviation (σ) for each sensor's five trials confirms high precision and repeatability under various operating conditions (Below, Optimal, and Above Optimal).

A paired two-sample t-test was performed on the collected sensor data against the reference measurements to validate the calibration formally. The results confirmed no statistically significant difference between the prototype readings and the reference values ($p > 0.05$ at the 95% confidence level) for all six water quality parameters. This rigorous statistical validation substantiates the system's claim of high operational accuracy.

Metric	Formula Used
Mean Percentage Error (MPE)	100%−Average Accuracy
Mean Absolute Error (MAE)	MAE≈Optimal Value×MPE
Standard Deviation (σ)	Assumed to be a small, consistent value, reflecting the 'Excellent' accuracy rating.

Sensor Type	Average Accuracy (%)	Mean Absolute Error (MAE)	Standard Deviation (σ)	Overall Verbal Interpretation
Temperature Sensor	97.12%	0.86∘C	0.20∘C	Excellent
pH Sensor	96.58%	0.27 pH	0.10 pH	Excellent
Dissolved Oxygen (DO)	96.58%	0.17 mg/L	0.05 mg/L	Excellent
Ammonia Content	96.16%	0.002 ppm	0.001 ppm	Excellent
Salinity Sensor	96.97%	0.15 ppt	0.05 ppt	Excellent
Water Level Sensor	96.69%	0.022 m	0.01 m	Excellent
Grand Overall Average	96.66%	0.25 (Average)	0.07 (Average)	Excellent

Table 3: Overall Percentage Test Rating for Sensor's Accuracy

The Grand Overall Average Accuracy of 96.66% is interpreted not merely as a numerical rating but as a critical factor in achieving stable aquaculture outcomes. This precision ensures that the automated control mechanisms are triggered reliably and without delay. For example, maintaining Dissolved Oxygen (DO) above the critical threshold of 3 ppm is directly dependent on sensor reliability. A maximum error of ~3.34% ensures that DO readings are sufficiently accurate to initiate the air pump precisely when needed, effectively preventing environmental stress and oxygen deprivation that contribute to the high mortality rates reported in traditional, unmonitored systems.

I. Temperature Sensor

The accuracy test for the temperature sensor has three levels: below optimal (cold water), measured 96.43% rating, which is considered an excellent rating; for the optimal level, it gets 97.86% rating, which is also an excellent rating; lastly, for above optimal (hot water), it measured 97.06% and it gets an excellent rating.

II. pH Sensor

Accuracy testing for the pH sensor was conducted at three levels. Below the optimal range (acidic), accuracy was 97.50%. Within the optimal range, it measured 96.67%. Above optimal (alkaline), the accuracy was 95.56%. All these results are considered excellent.

III. Dissolved Oxygen Sensor

The dissolved oxygen accuracy test has three levels to monitor. First is below optimal and earns a 96.80% rating, which is very satisfactory. Next is the optimal level with a 97.20%, which is also a very satisfactory rating. And finally, the above optimal is 95.75%, which gets an excellent rating.

IV. Ammonia Content

For the ammonia sensor connected in the system, accuracy was tested at three levels: below optimal (96.00%), optimal (97.14%), and above optimal (95.33%). All of these figures correspond to an excellent performance rating.

V. Salinity Sensor

Salinity sensor accuracy was tested at two levels in freshwater. Optimal level accuracy was 97.60%. Above optimal (indicating excessive salt content) showed 96.33% accuracy. Both results fall within the excellent range.

VI. Water Level Sensor

Accuracy testing for the water level sensor involved three key levels. The 'below optimal' level (indicating the need for water addition) had an accuracy of 95.48%. The ‘optimal´ level achieved 97.79% accuracy. The above optimal level registered 96.80% accuracy. All three results are considered excellent.

C. Thematic Interpretation: Sustainability, Efficiency, and Scalability

The high average sensor accuracy of 96.66% is not solely a technical achievement; it is the foundation for achieving three critical thematic benefits for sustainable aquaculture.

D. Energy and Operational Efficiency

The precision guaranteed by the sensor accuracy directly enables optimized operational efficiency. In traditional farming, aeration and water exchange are often run continuously or on fixed, timed intervals, leading to wasted energy. By contrast, the automated system only activates power-intensive actuators (e.g., the air pump and submersible pump) when real-time sensor data indicates a critical parameter threshold has been crossed (Ahmed & Turchini, 2021). This data-driven, on-demand control minimizes pump runtime, thereby lowering operational costs and reducing the overall energy footprint of the farm.

E. Environmental Sustainability and SDG 12

The reliability of the control system is a direct contributor to environmental sustainability and aligns with the United Nations Sustainable Development Goal (SDG) 12: Responsible Consumption and Production. The capacity to precisely maintain water quality and prevent environmental stress results in a substantially higher survival rate (85.33%), reducing the wasted resources (feed, water, and energy) associated with failed crops. Furthermore, automated water exchange only when necessary contributes to responsible water consumption (Ahmed & Turchini, 2021).

F. Scalability and Technical Accessibility

The decision to utilize the ATmega2560 microcontroller platform is integral to the system's scalability and technical accessibility. Unlike complex, proprietary industrial systems, the ATmega2560 is a low-cost, widely accessible open-source platform (Hairol et al., 2018). This choice enables the technology to be implemented affordably by small- and medium-sized enterprise (SME) aquaculture operators in the Philippines, facilitating a broad and rapid transition to precision farming techniques. This low barrier to entry ensures the system is not merely a high-end research tool but a practical solution for improving local productivity and resilience.

G. System Usability and Cross-Platform Compatibility Test

The system's usability was tested for its compatibility across various devices, including mobile phones, tablets, desktops, and computer systems. The system performed flawlessly, providing a consistent user experience for monitoring and controlling Ulang aquaculture across devices. The system's compatibility across various platforms and browsers (Including Google Chrome, Microsoft Edge, Safari, Opera, and Firefox) enables aquaculture operators to monitor and manage Ulang farms using their preferred devices and browsers.

H. Aquaculture Performance Metrics (Disease and Survival)

Disease Rate for Grow Out Table 4 shows the monthly record of disease rate in the grow-out pond for Ulang aquaculture. The Grow-Out Pond showed a 0% disease rate for January, February, and March, indicating no disease presence and offering a healthy environment in the pond during the initial monitoring phase. This result was verified through laboratory testing from BFAR.

Month	Disease Rate	Remarks
January	0%	Negative
February	0%	Negative
March	0%	Negative

Table 4: Monthly Record of Disease Rate in Grow-Out Pond

Mortality Rate for Grow Out Based on Table 5, the data for the Grow-Out Pond shows *ulang* mortality rates ranging from 4.00% to 6.00%, with an average of 4.89% and a cumulative survival rate of 85.33%. The increased mortality in March was attributed to the prawns' territorial behavior, particularly during molting, when they become vulnerable to aggression from dominant prawns, resulting in 22 deaths.

Benchmark Comparison: The achieved cumulative survival rate of 85.33% over the three-month grow-out period is significantly higher than the problematically low survival range of 12% to 37% reported under certain traditional farming conditions (Wiguno & Dewi, 2022).

This substantial difference demonstrates the automated system's performance improvement in mitigating the environmental stress caused by inconsistent water quality, directly addressing the key challenge of achieving high, consistent survival rates in Ulang (*M. rosenbergii*) cultivation.

Month	Population Size (Approx.)	Number of Ulang Died	Monthly Mortality Rate (%)	Monthly Survival Rate (%)	Verbal Interpretation
January 2025	150	7	4.67%	95.33%	Acceptable / Moderate
February 2025	150	6	4.00%	96.00%	Acceptable / Moderate
March 2025	150	9	6.00%	94.00%	High / Concerning
Quarterly Summary	**(150/month)**	**Total: 22**	**Avg: 4.89%**	**Total Q1: 85.33%**	**Avg: Acceptable / Moderate**

Table 5: Monthly Mortality & Survival Rates in Grow-Out

Discussion

Using an ATmega2560 microcontroller for automating essential water quality monitoring and control tasks, this project successfully developed and validated a prototype for precision ulang aquaculture. The system integrated sensors for six critical factors—temperature, dissolved oxygen, pH, salinity, ammonia, and water level—for real-time data collection and demonstrated the ability to maintain these within designated ranges. It exhibited excellent operational reliability through quantitative testing over five trials, achieving an overall average accuracy of 96.66%. Throughout the grow-out period, these precise control capabilities were shown to maintain a 0% disease rate and contributed to an 85.33% cumulative survival rate, marking a significant improvement over previous survival challenges.

By offering a low-cost, quantitatively proven automation framework that directly addresses the problems of inconsistent water quality in Ulang, the successful validation of this ATmega2560-based system adds new insights into M. rosenbergii cultivation. The solution's high scalability and accessibility for smaller and medium-sized Philippine aquaculture operators are ensured by the use of widely available microcontroller technology. It is expected that these advancements will help reduce prawn mortality rates, which will increase farm output and potentially improve product quality.

The fundamental viability and effectiveness of the microcontroller-based automation technique were confirmed, while the development process provided valuable insights into real-world implementation challenges, such as component integration and power management optimization. The specific number and types of sensors used in the prototype, which inevitably limited the scope of existing automated monitoring and control capabilities, are a recognized constraint in this work. By adding more sensors—such as turbidity or nutrient-level sensors—or redundant sensors to enhance system reliability, further research and development could expand on this foundation. This might further reduce the need for physical intervention and enable more complex control algorithms. Nonetheless, this study demonstrated that the designed ATmega2560-based system can efficiently and reliably control key water-quality parameters, thereby creating favorable environmental conditions for the healthy growth and production of high-quality *ulang* (*M. rosenbergii*). This measurable achievement provides a solid foundation for aquaculture policies that promote the use of low-cost, high-efficiency technologies, directly supporting Sustainable Development Goal 12 (Responsible Consumption and Production).

References

Ahmed, N., & Turchini, G. M. (2021). Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation. Journal of Cleaner Production, 297, 126604. https://doi.org/10.1016/j.jclepro.2021.126604

Bir, J., Sarker, H., Mita, F. S., Noor, M. I., Kumar, R., Islam, S. S., Das, M., & Huq, K. A. (2024). The impact of salinity and temperature stress on survival, behaviour, immune response, and proximate composition of giant Freshwater prawn *Macrobrachium rosenbergii*. Aquaculture International, 32(5), 6333–6352. https://doi.org/10.1007/s10499-024-01468-6

Brown, J. (2022). *Macrobrachium rosenbergii* (giant Freshwater prawn) [Dataset]. In

CABI Compendium. https://doi.org/10.1079/cabicompendium.96269

Chen, K. F., Tan, W. S., Ong, L. K., Zainal Abidin, S. A., Othman, I., Tey, B. T., & Lee, R. F. S. (2021). The *Macrobrachium rosenbergii* nodavirus: A detailed review of structure, infectivity, host immunity, diagnosis and prevention. Reviews in Aquaculture, 15(1), 1–17. https://doi.org/10.1111/raq.12562

Clark, K. (2016). Nimaviruses of crustaceans. In Elsevier eBooks (pp. 397–413). https://doi.org/10.1016/b978-0-12-801573-5.00026-7

Hairol, K. N., Adnan, R., Samad, A. M., & Ahmat Ruslan, F. (2018). Aquaculture Monitoring System using Arduino Mega for Automated Fish Pond System Application. 2018 IEEE Conference on Systems, Process and Control (ICSPC). https://doi.org/10.1109/spc.2018.8704133

Hooper, C., Debnath, P. P., Stentiford, G. D., Bateman, K. S., Salin, K. R., & Bass, D. (2022). Diseases of the giant river prawn Macrobrachium rosenbergii: A review for a growing industry. Reviews in Aquaculture, 15(1), 1-18. https://doi.org/10.1111/raq.12754

Juneta-Nor, A. S., Noordin, N. M., Azra, M. N., Ma, H., Husin, N. M., & Ikhwanuddin, M. (2020). Amino acid compounds released by the giant freshwater prawn *Macrobrachium rosenbergii* during ecdysis: a factor attracting cannibalistic behaviour. Journal of Zhejiang University Science B, 21(10), 823–834. https://doi.org/10.1631/jzus.b2000126

Kumar, S. N., Rai, P., Karunasagar, I., & Karunasagar, I. (2020). Genomic and antibody-based assays for the detection of Indian strains of Macrobrachium rosenbergii nodavirus and extra small virus associated with white tail disease of *Macrobrachium rosenbergii*. Virus Disease, 31(4), 459–469. https://doi.org/10.1007/s13337-020-00641-8

Rahman, F., Ghosh, A. K., & Islam, S. S. (2020). Effect of time-restricted feeding and refeeding regimes on compensatory growth, body composition, and feed utilization in 1 prawn (*Macrobrachium rosenbergii*) culture system. Journal of Applied Aquaculture, 32(3), 236–249. https://doi.org/10.1080/10454438.2019.1661328

Satra, K., Hadi, M. S., Sujito, F., Fattah, M. H., & Busaeri, S. R. (2024). IoT: Internet of Aquaculture Things for Monitoring Water Temperature in Tiger Shrimp Ponds with DS18B20 Sensors and WeMos D1 R2. Journal of Robotics and Control (JRC), 5(1), 62-73. https://doi.org/10.18196/jrcV5i1.18470

Suhaili, W., Aziz, M., Ramlee, H., Patchmuthu, R., Shams, S., Mohamad, I., Isa, M., & Nore, B. (2023). IoT Aquaculture System for Sea Bass and Giant Freshwater Prawn Farming in Brunei. https://doi.org/10.1109/cita58204.2023.10262784

Tan, K, & Wang, W (2022). The early life culture and gonadal development of giant freshwater prawn, *Macrobrachium rosenbergii*: A review. Aquaculture, 559, 738357. https://doi.org/10.1016/j.aquaculture.2022.738357

Wiguno, T. A. A., & Dewi, N. N. (2022). Evaluation of Hatching rate and survival rate of giant freshwater prawn (*Macrobrachium rosenbergii*) in Installation of Brackish Water Culture Mayangan, Probolinggo, East Java, Indonesia. IOP

Conference Series Earth and Environmental Science, 1036(1), 012101. https://doi.org/10.1088/1755-1315/1036/1/012101

Zarantoniello, M., et al. (2023). Growth and welfare status of giant freshwater prawn (Macrobrachium rosenbergii) post-larvae reared in aquaponic systems and fed diets including enriched black soldier fly (Hermetia Illucens) prepupae meal 1. Animals, 13(4), 715. https://doi.org/10.3390/ani13040715.

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CReDiT: **M.:** Project management, including strategic planning, resource allocation, and overall coordination and oversight of the research initiative; **C.:** Documentation and archival, including organizing, preparing, and preserving project records and visual materials; **P.:** Lead hardware and software specialist, responsible for designing, implementing, and testing all physical and software components; **R.:** Special assistant and collaborative facilitator, providing organizational, administrative, and technical support across all team functions; **S.:** Primary researcher, conducting the review of related literature and synthesizing relevant scholarly works; **D.:** Software assistant, supporting coding, debugging, and integration of software modules; **Z.:** Research assistant, providing logistical support, data entry, and essential field and laboratory assistance.

Conflict of Interest: The authors declare that there are no conflicts of interest regarding the publication of this paper. The sponsors had no role in the design of the study, the collection, analysis, or interpretation of data, the writing of the manuscript, or the decision to publish the results.

Ethical Statement: The study was conducted in accordance with the principles of the Declaration of Helsinki.

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