Intelligent IoT-enabled data analytics and monitoring framework for smart freshwater recirculating aquaculture systems

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Abstract

The global population is 8.1 billion and continues to expand, resulting in a greater need for food. Fish is an abundant resource for minerals, antioxidants, proteins, and micronutrients. It is a crucial component of nutrition for customers, particularly in impoverished and developing nations. It is a significant difficulty for farmers to meet consumer demand for nutritious seafood. A recirculating aquaculture system (RAS) serves as a mechanism to bridge the disparity between seafood production and consumption. The use of regulated conditions for RAS production has significantly risen; nonetheless, substantial losses occur due to laborious technology and managerial failures. Agricultural producers need timely and precise data to oversee and optimize output capacity. This study presents a smart freshwater recirculating aquaculture system (SF-RAS) using an IoT-enabled data analytics and monitoring framework (IoT-DAMF). The suggested system incorporates sensors and controllers. The network of sensors oversees aquatic variables, while controllers regulate the RAS ecosystem. An advanced DAMF significantly contributed to the oversight and preservation of the SF-RAS. The analysis established the correlation among the aquatic characteristics and revealed the corresponding variation. The empirical assessment indicates that the proposed method exhibits the best correlation for tracking relative changes in RAS characteristics.

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Introduction

Aquaculture, commonly called aqua farming, involves developing, rearing, and capturing fish, algae, bacteria, and many other species. It is also characterized as the propagation of organisms that thrive in aquatic environments under regulated circumstances (Føre *et al.,* 2023). Aquaculture is a dependable and environmentally sustainable method for generating superior protein for human consumption. This procedure is more effective than other agricultural methods due to superior food conversion rates (Tolentino *et al.,* 2020). Aquaculture and Fisheries have gained global prominence (Gandomkar *et al.,* 2022).

RAS are terrestrial-intensive fish farming systems that recycle water, often via physical and biological processes, to minimize water usage while ensuring sufficient water quality (Su, Sutarlie and Loh, 2020). RAS employs contemporary insights from biological sciences, environmental studies, mechanics, and data science. Recycled water is used repeatedly, with a minimal fraction substituting fresh water (Xiao *et al.,* 2019). A diverse array of aquatic and freshwater organisms is cultivated in RAS from hatching to grow-out stages (David Winster Praveenraj *et al.,* 2024; Papadopoulos and Christodoulou, 2024).

RAS has been employed for many years in fish cultivation, but only a limited number of extensive systems, producing over 14 million kg annually, are now operational (Kulkarni and Jain, 2023). The concept of RAS originated from Japanese ecological purifying techniques in the 1970s (Boopathy *et al.,* 2024). Since 1995, biological science, robotics, bottom release, and regulation of dissolved oxygen (DO) and temperature have been used (Nithya *et al.,* 2020). The present focus of RAS advancement is enhancing the purity of water devices and technologies, long-term viability, and the quality of wastewater outflow (Kaur and Chandra, 2024; Agarwal and Yadhav, 2023).

Nevertheless, due to RAS's price and energy intensity, recommendations have been proposed to enhance their economic efficiency. Water conditions may be classified into physical characteristics, dissolved substances, physiological pollutants, and diseases Chun *et al.,* 2018; Alamer and Shadadi, 2023). Physical factors are contingent upon climate and environmental variables. Water quality supervision is a crucial component of aquaculture, particularly in RAS, where water is continuously cycled inside the system (Singh *et al.,* 2023).

The primary metrics for quality control encompass pH, the environment, oxidation-reducing capacity (O-R), fluidity, saltiness, and DO (Prakash and Khanna, 2024). Optimal water quality may promote fish development and decrease the prevalence of fish illnesses (Shi *et al.,* 2024). Therefore, techniques capable of swift, immediate, and intelligent surveillance and data storage are essential. The paper introduces an intelligent IoT-enabled freshwater RAS. The suggested approach efficiently regulates the ideal requirements for the aquaculture sector (Badii *et al.*, 2013; Karimov and Bobur, 2024).

Proposed Method

The hardware layer is tasked with collecting information from the devices. System-integrated sensing devices collect water quality indicators while controllers regulate those factors. The sensor units of the suggested system are equipped with analog-based DO, pH, EC, real-time clock (RTC) timer, and temperature sensors. The sensor components are positioned on the exterior of the fish farming facilities. BeagleBone Black chose it for edge computing (EC) and connectivity. The EC device has many versatile input and output interfaces, facilitating access to diverse networking interface standards. The inbuilt 4-GB local flash drive offers enough capacity for data organization under the relational database paradigm. The controller has a 1-GHz ARM Core CPU, which utilizes little power while delivering sufficient computing capacity. Transducers have been used to sustain a viable aquaculture ecosystem, including air intakes, underwater pumps, bio-filters, heating systems, and gates. Figure 1 illustrates the design of the suggested IoT-DAMF for SF-RAS.

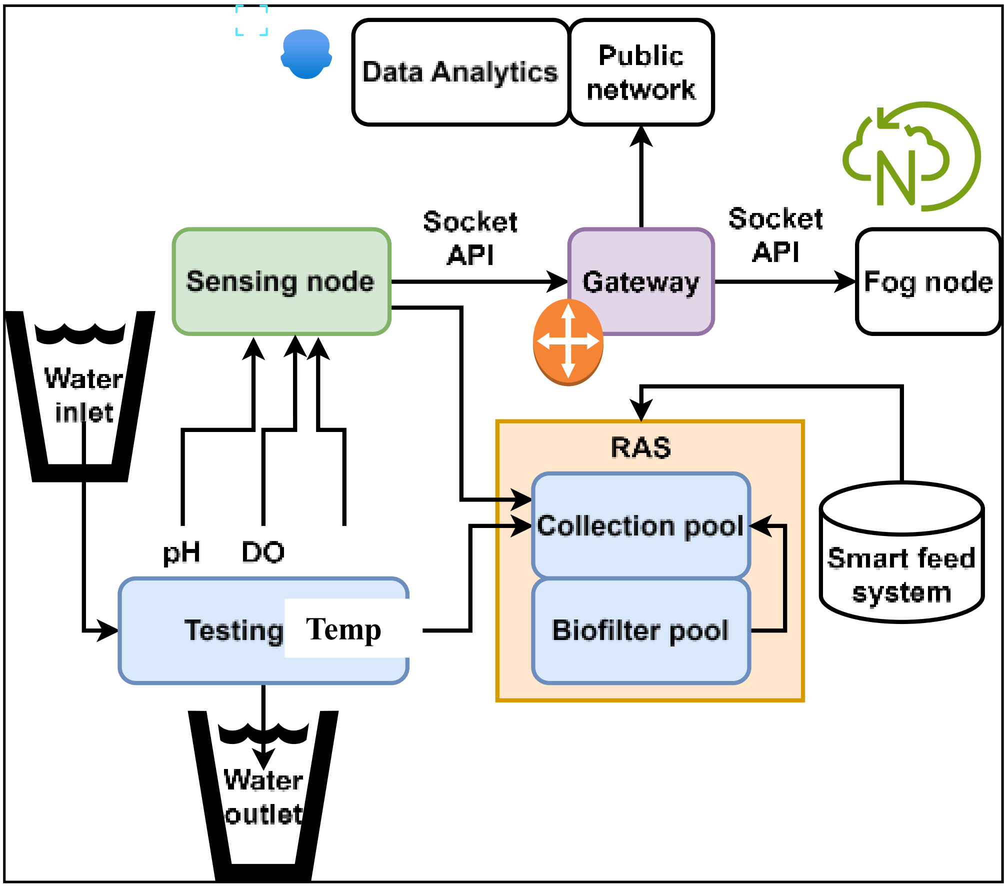

Figure 1: Architecture of the proposed IoT-DAMF for SF-RAS.

Testing Site and Sensors

The suggested system architecture includes an EC node outfitted with temperature, pH, DO, and temperature sensors. Transducers have been used to sustain a viable RAS system, including air intakes, underwater pumps, bio-filters, heating systems, and gates. All detectors, except for the temperature sensor, are positioned outside the primary collecting tank, as seen in Figure 1. This configuration safeguards the sensor's tip against rusting and prolongs its lifespan. The combined actuator, consisting of an underwater pump and gate, enables water to flow from the primary tank to the testing site. After the water assessment, the valve connected to the cylindrical funnel discharges the water. A non-invasive water depth sensor controls the gate's opening and closing, and an underwater pump controls the excess water in the curved vortex. Following each water-related evaluation, purified water is used to cleanse the sensor probe. The water test for quality is programmed via an RTC timer (Sharma and Iyer, 2023). The qualitative research established that the water quality in the cultivation pond remains stable. Various variables, including water temperature, meteorological conditions, method of feeding, and the release of waste products, affect the water's purity. These measurements often demonstrate variation at various intervals all through the day. After analyzing a month's collected data, we developed an appropriate timetable for managing the SF-RAS.

Smart Feed System (SFS)

An essential component of the RAS is tracking fish feeding precisely. Skipping appropriate food administration might adversely impact the overall health of the fish. Excessive feeding leads to fish's demise and increases the concentration of food-derived contaminants in the water. This excessive feeding exacerbates the accumulation of ejected contaminants in the water, increasing the levels of detrimental nitrogen and ammonium. Both these compounds provide considerable risks to the well-being of fish. During the night, unconsumed algae deplete DO and release elevated carbon dioxide (CO_2) levels into the aquatic ecosystem.

In contrast, analogous algae emit DO due to photosynthesis during sunlight. To maintain the homeostasis of the RAS environment, it is essential to provide suitable feed. The consequences of excessive feeding and the extended presence of leftover substances in the water may significantly impact water quality. Algae in green are soluble in water and easily ingested by fish, serving a crucial function in their nutrition. Figure 1 illustrates that the SFS consists of a submerged pump and a stirring device. The stirrers efficiently mix the green algae solution, which the underwater pump conveys to the collecting pool.

The RAS cleans the germinated water and then reuses it after appropriate disinfection. This RAS efficiently directs water via bio-filters that remove waste products from aquatic creatures and decaying matter in the water. The lack of technical assistance impedes aquaculture producers in their endeavors to independently monitor and maintain the health of the water. In exposed water aquaculture, the water is contaminated with various waste substances. The leftover particles decompose, consequently affecting the general quality of the water.

This RAS arrangement conveys water from the gathering units to the bio-filter compartment by pumps. The cleansed water is then redirected into the primary tank. This recirculation process commences after every feeding round.

The novel RAS design proficiently tackles the principal challenge of the ammonia level and modulates the pH value.

IoT-DAMF

The IoT-DAMF architecture includes a communication structure that links detection sensor nodes, fog computing (FC) nodes, and gateway, as seen in Figure 1. The socket connectivity API enables the transmission of sensor information and manages interactions between EC and FC nodes. The gateway facilitates interaction between both private and public networks. The location of FC nodes is crucial for DAMF in the suggested network architecture. F C nodes own regional datasets and analytical algorithms for processing information. The FC node regulates the planned surveillance and administration activities. The Amazon Web Services (AWS) infrastructure operates a similar internet server.

Local information processing to the sensor node facilitates optimum system maintenance, guaranteeing compliance with planned DAMF activities. The current capacity of the open-source cloud requires enhancement to tackle issues like delay and bandwidth limitations adequately (Becke *et al.*, 2019). Exclusively depending on the cloud server for thorough analysis and oversight may result in unfavorable consequences. The possibility of communication disruptions between the sensor node and cloud-based servers increases the danger of compromising timely planned activities at the detecting node.

To address these issues, cloud analysis has been carefully placed nearer to the detection node via FC nodes, preventing interruptions to planned DAMF. Nonetheless, the FC nodes mostly function as information processing and retention mediators. The obligation to oversee the sustainable retention and processing of sensor information lies within the domain of the general-purpose cloud. The Rest API is the communication conduit for information and management inside the web server.

The IoT interface includes capabilities such as adjustment, finding defects, and state tracking for sensors and controllers. The DA shows the projected information in relation to the real information. This feature distinguishes between authentic sensing information and analytics-driven forecasted information. A unique and arbitrary API password has been used to protect the identification of each technology. The password is unique to each gadget in the network. The access code for the API is distinctive for each device inside a network.

Results

The sensors react to command signals produced by the IoT-DAMF program. The technique employs historical data to forecast variations in DO levels, considering associated variables in water such as temperature and pH. Exclusively, depending on sensor information for system functionality may result in inaccurate management. Extended use of sensors often results in measurement errors. Notwithstanding inconsistencies in sensor readings, we mitigate departures from the ideal condition by analyzing prior data acquired at analogous times. Temperature and absolute pH characteristics have been evaluated to forecast DO levels. The interrelated characteristics of DO and temperature have also been recorded to predict pH levels. To assess the accuracy of the DO sensor results, we juxtapose the pH and temperature measurements with records from comparable periods.

Table 1: Correlation coefficient analysis for IoT-DAMF in SF-RAS.

Factors	pH	DO	Temp
pH	1	0.74	0.835
DO	0.74	1	0.512
Temp	0.835	0.512	1

The correlation study for IoT-DAMF in SF-RAS in Table 1 reveals substantial interconnections among critical water quality parameters: pH, DO, and Temperature (Temp). The association between pH and dissolved oxygen (DO) is reasonably robust at 0.74, suggesting that variations in pH levels significantly affect DO concentration. Additionally, pH has a robust positive association with temperature (0.835), indicating that higher water temperatures are often linked to increased pH levels. This robust correlation underscores the necessity for real-time temperature monitoring and regulation to sustain optimal pH levels in intelligent aquaculture systems. The connection between DO and temperature is moderate (0.512), suggesting that temperature fluctuations significantly influence oxygen solubility, but to a lesser extent than the pH-temperature association. This mild association illustrates the established phenomena wherein elevated temperatures often diminish the dissolved oxygen levels in aquatic ecosystems, impacting fish health and overall system production. The correlation matrix highlights the interrelatedness of water quality metrics, emphasizing the need for integrated IoT-based DAMF systems to guarantee optimum functioning and sustainability in SF-RAS ecosystems.

Conclusion

This research introduces a sophisticated freshwater recirculating aquaculture system (SF-RAS) using an Internet of Things-enabled data analytics and monitoring framework (IoT-DAMF). The proposed system integrates sensors and controls. The sensor network monitors water parameters while controllers manage the RAS environment. A sophisticated DAMF greatly facilitated the management and conservation of the SF-RAS. The investigation identified the association between the aquatic features and demonstrated the associated variance. The empirical evaluation demonstrates that the suggested technique achieves optimal accuracy in monitoring relative changes in RAS properties. The correlation between pH and dissolved oxygen (DO) is substantial at 0.74, indicating that fluctuations in pH levels considerably influence DO concentration. Moreover, pH strongly correlates with temperature (0.835), suggesting that elevated water temperatures are often associated with higher pH values. This strong association highlights the need for real-time temperature monitoring and control to maintain ideal pH levels in advanced aquaculture systems.

References

Agarwal, A. and Yadhav, S., 2023. Structure and functional guild composition of fish assemblages in the Matla Estuary, Indian Sundarbans.

Aquatic Ecosystems and Environmental Frontiers, 1(1), pp.16–20.

Alamer, L. and Shadadi, E., 2023. DDoS attack detection using long-short term memory with bacterial colony optimization on IoT environment. *Journal of Internet Services and Information Security, 13*(1), pp.44–53. https://doi.org/10.58346/JISIS.2023.I1.005

Badii, A., Carboni, D., Pintus, A., Piras, A., Serra, A., Tiemann, M. and Viswanathan, N., 2013. CityScripts: Unifying Web, IoT and smart city services in a smart citizen workspace. *Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications, 4*(3), pp.58–78. https://doi.org/10.22667/JOWUA.2013.09.31.058

Becke, C., Schumann, M., Steinhagen, D., Rojas-Tirado, P., Geist, J. and Brinker, A., 2019. Effects of unionized ammonia and suspended solids on rainbow trout (Oncorhynchus mykiss) in recirculating aquaculture systems. *Aquaculture, 499*, pp.348–357. https://doi.org/10.1016/j.aquaculture.2018.09.048

Boopathy, E.V., Shanmugasundaram, M., Vadivu, N.S., Karthikkumar, S., Diban, R., Hariharan, P. and Madhan, A., 2024. LoRaWAN based coal miners rescue and health monitoring system using IoT. *Archives for Technical Sciences, 2*(31), pp.213–219. https://doi.org/10.70102/afts.2024.1631.213

Chun, S.J., Cui, Y., Ahn, C.Y. and Oh, H.M., 2018. Improving water quality using settleable microalga Ettlia sp. and the bacterial community in freshwater recirculating aquaculture system of Danio rerio. *Water Research, 135*, pp.112–121. https://doi.org/10.1016/j.watres.2018.02.007

David Winster Praveenraj, D., Prabha, T., Kalyan Ram, M., Muthusundari, S. and Madeswaran, A., 2024. Management and sales forecasting of an e-commerce information system using data mining and convolutional neural networks. *Indian Journal of Information Sources and Services, 14*(2), pp.139–145. https://doi.org/10.51983/ijiss-2024.14.2.20

Føre, M., Alver, M.O., Frank, K. and Alfredsen, J.A., 2023. Advanced technology in aquaculture–smart feeding in marine fish farms. *In Smart Livestock Nutrition*, (pp.227–268). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-22584-0_9

Gandomkar, H., Nazari, S., Hosseini, P. and Abdolhay, H.A., 2022. Genome-wide assessment and characterization of simple sequence repeats (SSRs) makers for Capoeta aculeata (Valenciennes, 1844) using NGS data. *International Journal of Aquatic Research and Environmental Studies, 2*(2), pp.16–28. https://doi.org/10.70102/IJARES/V2I2/4

Karimov, Z. and Bobur, R., 2024. Development of a food safety monitoring system using IoT sensors and data analytics. *Clinical Journal for Medicine, Health and Pharmacy, 2*(1), pp.19–29.

Kaur, K. and Chandra, G., 2024. Demographic data gaps and the challenges of population modeling in low-resource settings. *Progression Journal of Human Demography and Anthropology*, *2*(1), pp.13–16.

Kulkarni, P. and Jain, V., 2023. Smart agroforestry: Leveraging IoT and AI for climate-resilient agricultural systems. *International Journal of SDG's Prospects and Breakthroughs, 1*(1), pp.15–17.

Nithya, S., Sangeetha, M., Prethi, K.A., Sahoo, K.S., Panda, S.K. and Gandomi, A.H., 2020. SDCF: A software-defined cyber foraging framework for cloudlet environment. *IEEE Transactions on Network and Service Management*, *17*(4), pp.2423–2435. https://doi.org/10.1109/TNSM.2020.3015657

Papadopoulos, G. and Christodoulou, M., 2024. Design and development of data driven intelligent predictive maintenance for predictive maintenance. *Association Journal of Interdisciplinary Technics in Engineering Mechanics, 2*(2), pp.10–18.

Prakash, S.A. and Khanna, G., 2024. Superhydrophobic coatings in membrane technology: Enhancing oil-water separation. *Engineering Perspectives in Filtration and Separation*, *2*(3), pp.16–19.

Sharma, A. and Iyer, R., 2023. AI-powered medical coding: Improving accuracy and efficiency in health data classification. *Global Journal of Medical Terminology Research and Informatics*, *1*(1), pp.1–4.

Shi, S., Caluyo, F., Hernandez, R., Sarmiento, J. and Rosales, C.A., 2024. Automatic classification and identification of plant disease identification by using a convolutional neural network. *Natural and Engineering Sciences, 9*(2), pp.184–197. https://doi.org/10.28978/nesciences.1569560

Singh, M., Sahoo, K.S. and Gandomi, A.H., 2023. An intelligent-IoT-based data analytics for freshwater recirculating aquaculture system. *IEEE Internet of Things Journal, 11*(3), pp.4206–4217. https://doi.org/10.1109/JIOT.2023.3298844

Su, X., Sutarlie, L. and Loh, X.J., 2020. Sensors, biosensors, and analytical technologies for aquaculture water quality. *Research*. https://doi.org/10.34133/2020/8272705

Tolentino, L.K.S., De Pedro, C.P., Icamina, J.D., Navarro, J.B.E., Salvacion, L.J.D., Sobrevilla, G.C.D. and Madrigal, G.A.M., 2020. Development of an IoT-based intensive aquaculture monitoring system with automatic water correction. *International Journal of Computing and Digital Systems, 10*, pp.1355–1365.

Xiao, R., Wei, Y., An, D., Li, D., Ta, X., Wu, Y. and Ren, Q., 2019. A review on the research status and development trend of equipment in water treatment processes of recirculating aquaculture systems. *Reviews in Aquaculture, 11*(3), pp.863–895. https://doi.org/10.1111/raq.12270