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IoT-Enabled Raceway System for Sustainable Fish Culture in Hilly Environments

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Aquaculture in hilly landscapes provides both opportunities and challenges due to the region's rugged terrain, unpredictable climatic conditions, and limited availability of resources. Raceway culture, which uses elongated, narrow channels with continuous water flow resembling natural streams, has proven effective for fish culture in such environments. This system is mostly suitable for cold-water species, as the uniform flow maintains sufficient oxygen levels while efficiently removing waste (Minahal et al., 2024). Nevertheless, maintaining desirable water quality, appropriate water flow rates, and feed utilization in these regions required continuous monitoring and flexible management. The adoption of Internet of Things (IoT) technologies can significantly strengthen raceway operations by providing real-time measurement and evaluation of parameters such as dissolved oxygen, pH, temperature, turbidity, and ammonia (Chandramenon et al., 2024). Sensor installed within the channels can provide data to centralized platforms, allowing early detection of water quality fluctuations, refinement of feeding regimes, and automation of aeration or water exchange processes. Considering the difficult terrain, durable system designs incorporating solar-powered, wireless communication, and weather-resistant sensor enclosures are necessary. By combining eco-friendly aquaculture practices with smart monitoring systems, raceway aquaculture in hilly areas can achieve higher productivity, lower fish mortality, minimize dependency on manual interventions, and promote efficient use of water resources. Such an integrated framework not only improves the livelihoods of hill communities but also supports sustainable and environmentally sound aquaculture growth.

Raceway Systems in Aquaculture

Through constant water circulation, raceway systems offer a regulated aquatic habitat that closely resembles natural riverine conditions (Ramli, 2024). According to Nayoun et al. (2024), they are often made of concrete or high-density polyethylene and are elongated, shallow channels with unidirectional water flow. This constant flow creates advantageous conditions for animals that are acclimated to flowing water by replenishing dissolved oxygen and eliminating metabolic wastes. Raceways can support comparatively high stocking densities because of the constant flushing and aeration, which is beneficial for intensive aquaculture operations (Mahamuni & Goud, 2023). By reducing the buildup of toxic materials, the unidirectional circulation also helps to preserve the quality of the water and, eventually, reduces stress levels in the fish kept in captivity (Nagothu et al., 2024). These systems significantly lower disease outbreaks and fish mortality linked to low oxygen, an imbalanced pH, or high levels of ammonia, nitrite, and nitrate by maintaining constant water parameters (Sohail et al., 2023). The natural gradient of the land can be efficiently used to maintain water flow in hilly locations, reducing the energy requirements of pumping systems that are frequently seen in plain areas. Raceways are especially well-suited to such environments because they not only minimise operating expenses but also the carbon footprint (Nagothu et al., 2024). However, in order to guarantee sustainable operation and long-term productivity, the variable conditions of hilly regions such as fluctuating water availability, temperature extremes, and lake of transport system require sophisticated monitoring and management strategies (Laktuka et al., 2023; Mihály-Karnai et al., 2025).

Challenges of Fish Culture in Hilly Environments

Hilly areas present special difficulties for fish farming, including erratic water supplies, vulnerability to harsh weather conditions, and a lack of infrastructure and expert assistance. Transporting feed, machinery, and harvested produce is made more difficult by the rough terrain, which raises operational costs and logistical challenges. Furthermore, the remoteness of many locations frequently makes it more difficult to get specialised treatments and diagnostic facilities, which makes illness prevention and management more challenging. The necessity of dependable, real-time monitoring systems is highlighted by the need to balance fish health and water quality control in such remote areas.

A feasible option is provided by the use of Internet of Things (IoT) technologies, which turn traditional raceway systems into intelligent aquaculture facilities by facilitating automated regulation, predictive analysis, and continuous data collection (Kassem et al., 2021). To lessen fish stress and enhance growth in extremely variable conditions, IoT integration enables the precise regulation of critical factors, including temperature, pH, ammonia, and dissolved oxygen. Stable culture conditions are guaranteed even in the face of abrupt environmental changes through real-time monitoring and automated aeration, water flow, and feeding modifications. In environments where manual intervention is challenging and time-consuming, this proactive management improves aquaculture operations' resilience.

Cloud-based solutions also make it easier to access system data remotely, which enables farmers to make prompt and well-informed decisions without having to be there in person (Nayoun et al., 2024). In addition to streamlining operations, this kind of remote supervision improves fish growth and survival by facilitating early detection of disease outbreaks or deteriorating water quality (Flores-Iwasaki et al., 2025). According to Nayoun et al. (2024), IoT-driven aquaculture offers a more sustainable and efficient alternative by decreasing reliance on labour-intensive procedures and the expenses related to manual monitoring. By preserving resources and reducing the likelihood of contamination, this technological change ultimately advances financial success and environmental sustainability (Abdullah et al., 2024).

IoT Integration in Raceway Systems

The integration of Internet of Things (IoT) technologies into raceway aquaculture represents a major advancement in the sector, as it enables continuous, real-time monitoring and regulation of key environmental parameters essential for fish health and productivity (Nagothu et al., 2024). An IoT-enabled raceway system typically comprises sensors, actuators, communication modules, and a central data-processing unit, which function collectively to maintain favourable aquatic conditions and ensure comprehensive operational control (Tzu et al., 2024). Through these components, parameters such as water temperature, pH, dissolved oxygen, and fish behaviour can be monitored in real time, allowing automated adjustments and rapid decision-making to prevent the onset of unfavourable conditions (Huang & Khabusi, 2025; Mahamuni & Goud, 2023). For instance, aeration units may be activated or water flow altered immediately upon detection of deviations from optimal ranges, thereby ensuring stable and healthy environments for cultured species (Nagothu et al., 2024).

In addition to real-time control, the incorporation of artificial intelligence within IoT frameworks (AIoT) enables advanced data analytics, where deep learning and machine learning models interpret sensor data to predict water quality fluctuations and potential disease outbreaks (Ringø et al., 2025; Nagothu et al., 2024). Such predictive capabilities facilitate proactive management, reducing the risk of large-scale mortalities and improving efficiency by optimizing the use of feed, water, and energy (Hemal et al., 2024). Wireless connectivity further enhances the system by enabling remote monitoring and control, thus addressing the geographical challenges typically associated with aquaculture in hilly terrains. This integration not only enhances resilience and sustainability but also transforms conventional raceway systems into intelligent, data-driven aquaculture models capable of operating effectively in resource-limited and logistically demanding environments (Tina et al., 2025; Singh et al., 2024; Sohail et al., 2023).

A schematic representation of an IoT-enabled raceway system designed for optimal performance in hilly environments is presented below.

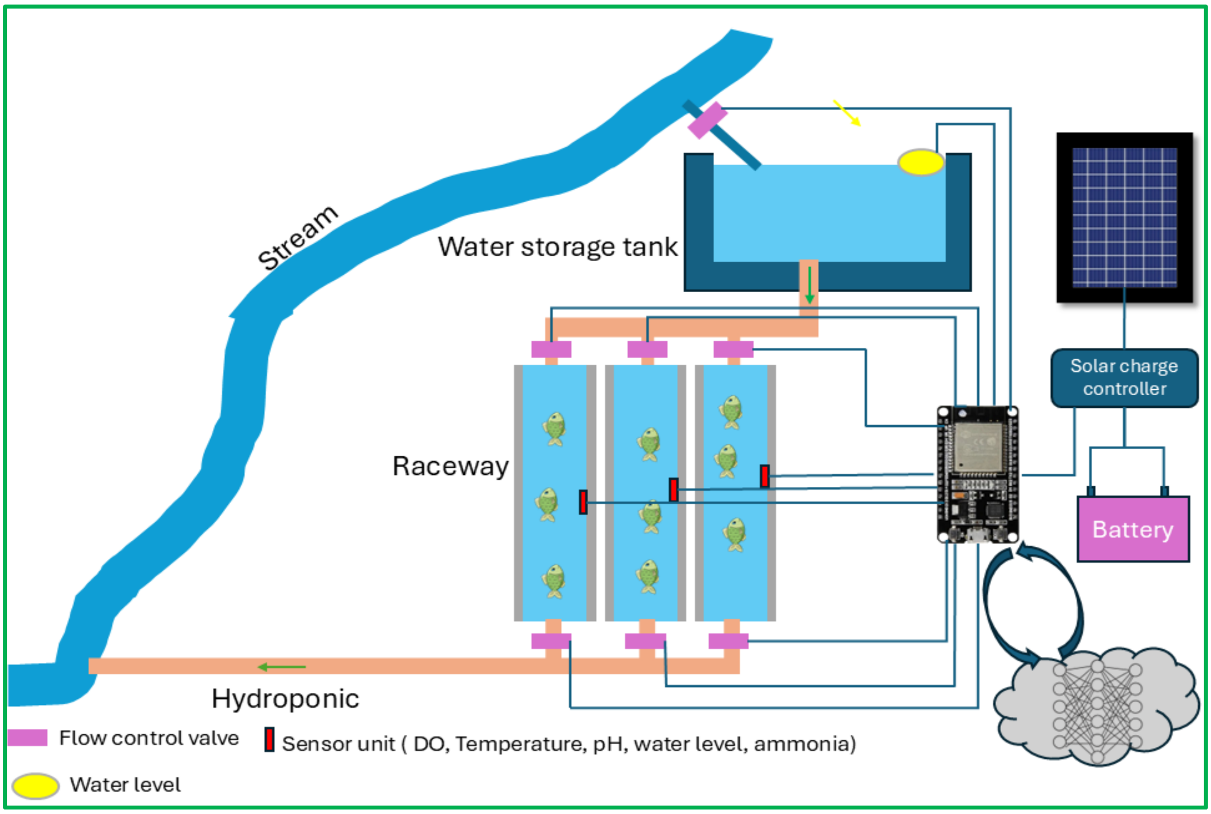

Figure 1. A schematic diagram showing the IoT-integrated raceway aquaculture system.

The provided schematic diagram consists of a water storage tank where hill stream water is collected as per requirement. Water from the storage tank is provided to the raceway system, where intensive fish are cultured. The system then employs a multi-sensor array within the raceway to continuously monitor crucial water quality parameters, transmitting this data wirelessly to a cloud where machine learning algorithms take necessary decisions. All these activities can be monitored with a computer. This real-time data accessibility and analytical capability allow for immediate intervention and proactive management of the aquatic environment, minimizing the risk of adverse conditions. The power requirement of the system is met by using a solar panel. This autonomous power source ensures uninterrupted operation in remote hilly areas, where traditional power grids may be unreliable or absent, further enhancing the system's sustainability and self-sufficiency.

Conclusion

This article underscores the transformative role of IoT-enabled raceway systems in overcoming the distinct challenges of aquaculture in hilly regions, demonstrating how integrated technologies can significantly improve efficiency and sustainability. Such systems offer reliable solutions for continuous monitoring and management of water quality, addressing earlier constraints related to technical complexity and data inconsistency. By leveraging real-time data acquisition and predictive analytics through fuzzy logic or machine learning models, farmers gain actionable insights that support the maintenance of optimal conditions for fish health and growth, while simultaneously lowering operational costs and minimizing environmental impacts. The combination of advanced sensing technologies with resilient communication protocols helps to overcome traditional limitations, ultimately enhancing productivity and fostering a more sustainable model of aquaculture.

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