Automated Flow-Rate Control in Intelligent Recirculating Aquaculture Systems (i-RAS) to Improve Water Quality, Energy Use, and Hybrid Catfish Growth

Dome Adoonsook*, Teppitag Boonta and Prasert Prasongphol

ABSTRACT

This study evaluated an automated flow-rate control system for hybrid catfish (*Clarias macrocephalus* × *C. gariepinus*) in a recirculating aquaculture system (RAS). The experiment employed a completely randomized design with four treatments, each replicated three times: an ammonia-sensor-driven variable flow (5–15 $m^3 \cdot h^{-1}$) and three fixed flow rates: low (0.5×), medium (1.0×), and high (1.5× tank volume·h^{-1}). Fish were stocked in circular tanks with a capacity of 3,500 L (3.0 m in diameter and 0.5 m in depth) at a stocking density of 100 fish·m^{-2}, with an initial average weight of 13–15 g·$fish^{-1}$. Fish were fed commercial pellets (≥30% protein) to apparent satiation twice daily and cultured for 16 weeks under continuous aeration and real-time monitoring of NH_3-N, dissolved oxygen (DO), temperature, and pH. After 16 weeks, the automated and high-flow treatments achieved the highest final weights (308.95±1.43 and 304.99±3.27 g) and survival rates (90.90±0.46 and 90.86±0.29%), which were significantly greater than those in the medium- and low-flow treatments ($p<0.05$). The automated system produced the lowest FCR (1.48±0.01; $p<0.05$) and maintained water quality (TAN, NH_3-N, NO_2^--N) comparable to the high-flow treatment, with TAN reduced by approximately 54% compared with the low-flow treatment ($p<0.05$). Energy consumption was reduced by approximately 25% compared with that of a constant high recirculation rate. These findings demonstrate that real-time, sensor-driven flow regulation can enhance fish growth, maintain water quality, and reduce energy demand, thereby improving the sustainability of RAS operations.

Keywords: Energy efficiency, Flow-rate control, Hybrid catfish, Recirculating aquaculture system (RAS), Water quality

INTRODUCTION

Aquaculture plays a crucial role in global food security as an affordable high-quality protein source, thus addressing food shortages worldwide (Pradeepkiran, 2019). Furthermore, aquaculture production constitutes over half of the aquatic animal products consumed worldwide, highlighting its increasing importance in meeting the growing food demand (FAO, 2022). However, traditional aquaculture systems such as earthen ponds or flow-through cages have inherent limitations in water quality, potentially affecting the growth and health of aquatic organisms. In particular, earthen ponds with limited water exchange can accumulate metabolic waste, including total ammonia nitrogen (TAN, comprising unionized ammonia nitrogen [NH_3-N], ammonium-nitrogen [NH_4^+-N]), and nitrite-nitrogen [NO_2^--N]), reaching toxic levels detrimental to fish health. Without adequate management, prolonged exposure to elevated TAN and NO_2^--N concentrations can induce stress, retard growth, and increase fish mortality rates (Bhatnagar and Devi, 2013). Additionally, maintaining water

Faculty of Fisheries Technology and Aquatic Resources, Maejo University, Chiang Mai, Thailand
*Corresponding author. E-mail address: dome_fb@hotmail.com
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quality in traditional pond systems often involves substantial water discharge, potentially causing environmental problems due to wastewater release into natural water bodies.

Recirculating aquaculture systems (RAS) help to overcome these issues, promoting sustainable aquaculture (Martins *et al*., 2010). RAS recycle and reuse water after physical and biological treatment, significantly reducing water consumption and consistently maintaining optimal water quality compared to open ponds. RAS technology is based on biological filtration (biofilters), whereby nitrifying bacteria convert TAN excreted by fish into NO_2^--N, and subsequently transform NO_2^--N into less toxic nitrate-nitrogen (NO_3^--N) (Martins *et al*., 2010). Consequently, water in RAS maintains consistently low TAN and NO_2^--N concentrations, ensuring safe conditions for aquatic organisms. Additionally, oxygen supplementation and proper pH control in RAS facilitate healthy growth at higher stocking densities, thereby lowering environmental impacts via minimal wastewater discharge (Pradeepkiran, 2019). Current advancements in RAS technology have allowed their application across various aquatic species, including freshwater fish, marine species, and shrimp (Chen *et al*., 2019).

Despite superior water quality management in RAS, determining optimal water recirculation rates remains critical for maximizing production efficiency. Variations in these rates influence waste removal efficiency and environmental conditions, directly affecting growth, survival, and stress levels in aquatic animals. Researchers have investigated the impact of different recirculation rates on aquaculture productivity, with research on white shrimp cultured in RAS indicating improved water quality (lower TAN and NO_2^--N) and enhanced growth rates with increased recirculation. However, shrimp survival rates peaked at the lowest recirculation rate, suggesting that excessively high recirculation rates may induce stress or introduce other influencing factors (Chen *et al*., 2019). Similarly, De León-Ramírez *et al*. (2022) demonstrated through experiments on tilapia cultured at different developmental stages (fingerling, juvenile, adult) under three water recirculation rates that optimal rates varied by fish age. Fingerlings performed best at moderate recirculation rates, juveniles at higher rates, and adults at moderate to lower rates. Inappropriate water recirculation rates can induce stress-related factors, such as suboptimal water quality or unsuitable water flow velocities, negatively affecting fish growth and health (De León-Ramírez *et al*., 2022). Moreover, Sühnel *et al*. (2024) reported that increasing water exchange rates to three times tank volume/hour improved waste removal and maximized survival in scallop (*Nodipecten nodosus*) larvae cultured in RAS, indicating that sufficient recirculation maintains optimal conditions for different life stages.

These studies underscore the necessity of identifying suitable recirculation rates within RAS to maintain safe water quality and optimize aquatic animal growth. Excessively low recirculation rates lead to hazardous TAN and NO_2^--N accumulation, reducing growth and increasing mortality, while excessively high rates may induce stress or cause unnecessary energy consumption (Chen *et al*., 2019; De León-Ramírez *et al*., 2022). Consequently, farmers should adjust recirculation rates based on stocking densities, species, and life stage to effectively manage water quality and energy utilization.

Currently, sensor technologies coupled with microcontrollers are used to manage automated water recirculation control in RAS, optimizing water conditions. Specifically, real-time NH_3-N monitoring via sensors and automatic pump or valve operation based on sensor readings enhance water quality control. For example, Li *et al*. (2023) implemented a dual-input fuzzy logic control system utilizing ammonia sensors to maintain safe NH_3-N levels (<2 ppm), even under high stocking densities, resulting in robust health and improved growth. These findings indicate that intelligent RAS, which adjust water recirculation rates based on real-time water quality data can enhance aquaculture sustainability and efficiency.

Additionally, recent studies highlight both the benefits and limitations of fully automated RAS. On the one hand, advanced sensor-driven RAS can significantly conserve water and improve fish health by maintaining stable water quality, thereby reducing mortality and enhancing growth (Flores-Iwasaki *et al*., 2025). Such systems have been reported to reuse over 90–95% of water and minimize effluent discharge, addressing environmental sustainability concerns (Tetreault *et al*., 2023). On the other hand, automated RAS can entail high energy consumption and substantial capital costs, and they require specialized technical expertise for operation and maintenance (Ahmed and Turchini, 2021). These challenges can hinder adoption by smaller producers, although ongoing technological advancements continue to improve the cost-effectiveness and reliability of intelligent RAS.

Considering the importance of recirculation rates for water quality and fish growth, this study evaluates the effectiveness of an intelligent recirculating aquaculture system (i-RAS) employing automated flow-rate control based on real-time NH_3-N measurements. The experiment compares three traditional fixed flow-rate RAS (0.5×, 1×, and 1.5× tank volume·h^{-1}) with a dynamically adjusted recirculation rate. Outcomes may determine optimal recirculation strategies for enhancing water quality management and growth in hybrid catfish (*Clarias macrocephalus* × *C. gariepinus*), contributing to sustainable and efficient aquaculture practices. This hybrid is one of Thailand's most important freshwater aquaculture species, with annual production exceeding 90,000 t, second only to tilapia, due to its rapid growth, tolerance to low oxygen levels and diseases, and high market demand (Chantasarn and Lawhavinit, 2018; Nuaunchun *et al*., 2020). However, its widespread use in high-density culture systems often results in deteriorating water quality, particularly elevated TAN and reduced dissolved oxygen (DO), which threaten health and productivity (Nuaunchun *et al*., 2020). Therefore, evaluating an i-RAS for this species is highly relevant for advancing sustainable aquaculture.

MATERIALS AND METHODS

Experimental fish

The experiment was conducted at the Faculty of Fisheries Technology and Aquatic Resources, Maejo University, Chiang Mai, Thailand. Hybrid catfish fingerlings (*Clarias macrocephalus* × *C. gariepinus*) weighing approximately 13–15 g·$fish^{-1}$ were selected for uniform size and acclimated in cement tanks for seven days with continuous aeration and feeding. Subsequently, the fingerlings were allocated into four experimental groups (treatments 1, 2, 3, and 4), each consisting of 700 fish·$tank^{-1}$.

I-RAS for hybrid catfish cultivation

The i-RAS comprised four independently operated units (Figure 1). Each experimental unit (Figure 2) included three plastic tanks (3,500-L capacity; 3.0 m diameter, 50 cm depth). Each tank had a 2-inch PVC overflow pipe connected to a drum filter system (mesh size 100 µm, drum diameter 30 cm, filtration area 0.2827 m^2). The drum filter was connected to a 200-L moving bed biofilm reactor (MBBR) containing 60 L of bio-media with specific surface area 900 $m^2 \cdot m^{-3}$. A 1-horsepower water pump (Mitsubishi, Model ACM-755T) and a 2-horsepower motor inverter (SAJ, Model PDH30) controlled water circulation and a flow rate of 400 L·min^{-1}. The water was also treated with an inline 30-watt UV sterilization unit.

The i-RAS control system (Figure 3) comprised a programmable logic controller (PLC) (Model Laink Kong, LK3U-32-10AD-2DA) that was managed through a 7-inch human- machine interface (HMI) touchscreen (Haiwell, Model B7H-W). The HMI displayed real-time data, enabled Wi-Fi connectivity, and facilitated control and data logging from various sensors installed within each culture tank, including an NH_3-N sensor, DO sensor, water temperature sensor, and pH sensor. Data were accessible via Haiwell Cloud and the associated mobile application (Figure 4).

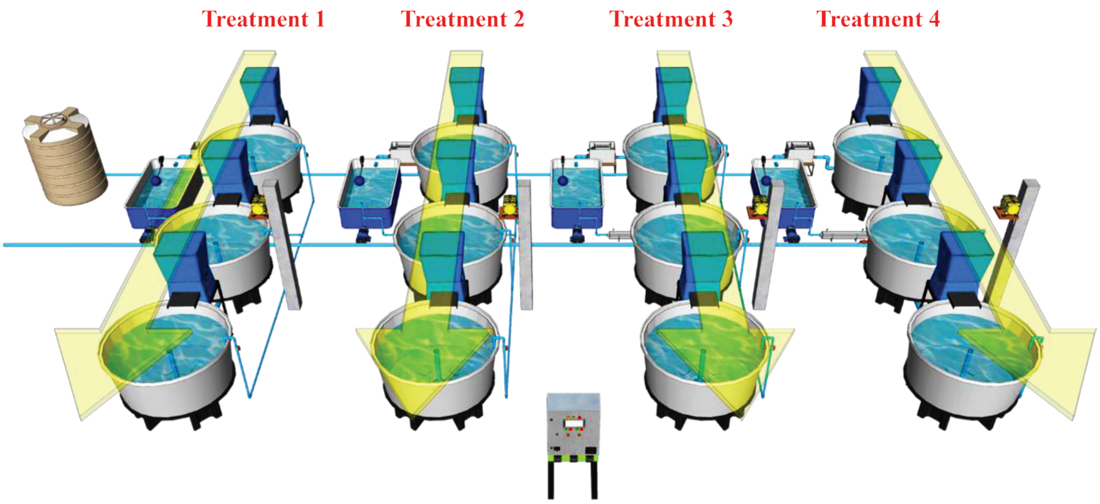

Figure 1. Experimental layout of the recirculating aquaculture system (RAS) treatments.

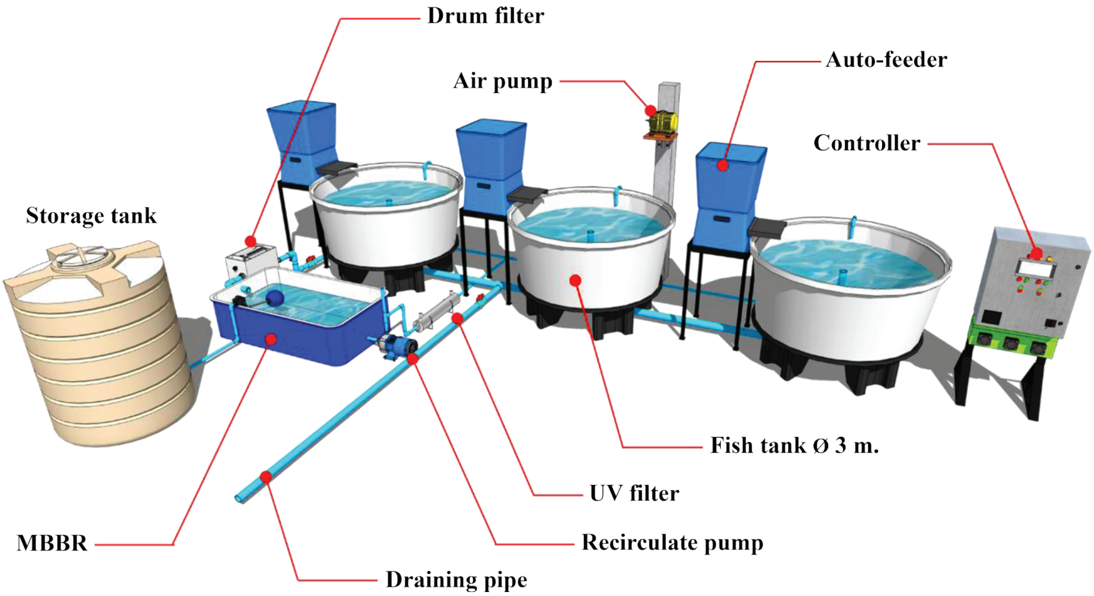

Figure 2. Schematic diagram of i-RAS components for one i-RAS system used for each treatment.

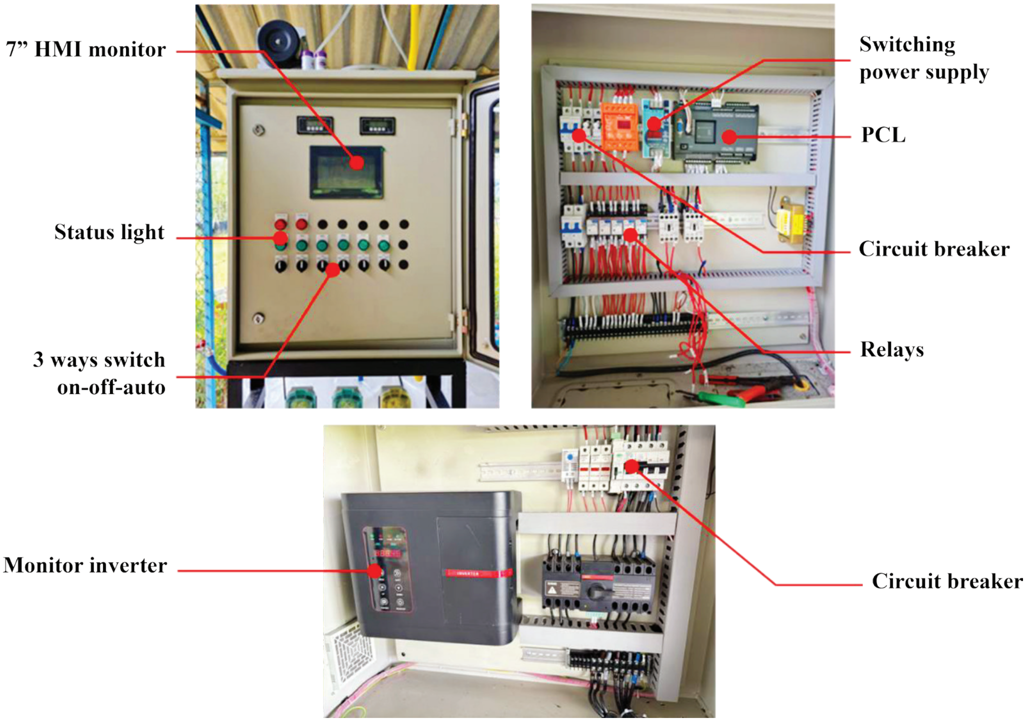

Figure 3. Components of the automatic RAS control system.

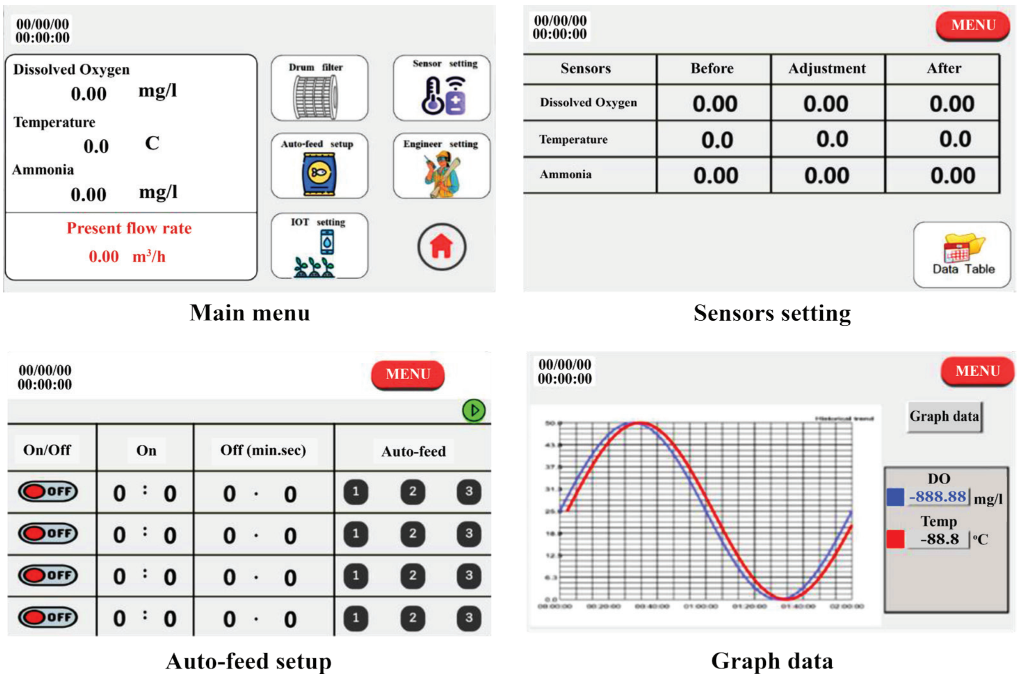

Figure 4. Water quality monitoring interface via HMI touchscreen and mobile application.

The water recirculation rate control system in the i-RAS comprised several essential components (Figure 5), including a real-time ammonia sensor (NH_3-N sensor) that transmitting analog signals to the PLC. The PLC processed and compared these readings with predefined control ranges, and then sent commands to the motor inverter to adjust the water pump motor speed, thereby achieving the desired flow rate. The control conditions were as follows (Figure 6): when NH_3-N concentrations were below 0.1 mg·L^{-1}, the water flow rate was set to 5 m^3·h^{-1}; when NH_3-N concentrations ranged from 0.1–0.2 mg·L^{-1}, the flow rate was adjusted to 10 m^3·h^{-1}; and when NH_3-N concentrations exceeding 0.2 mg·L^{-1}, the flow rate was increased to 15 m^3·h^{-1}.

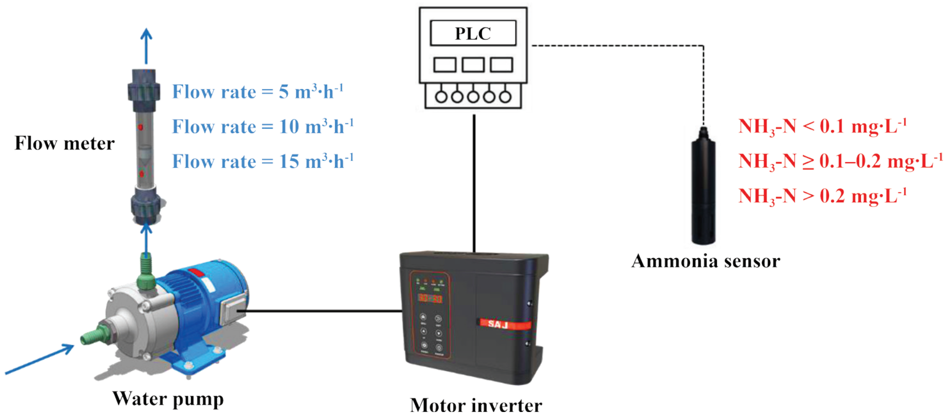

Figure 5. Automatic water recirculation rate control system components in i-RAS.

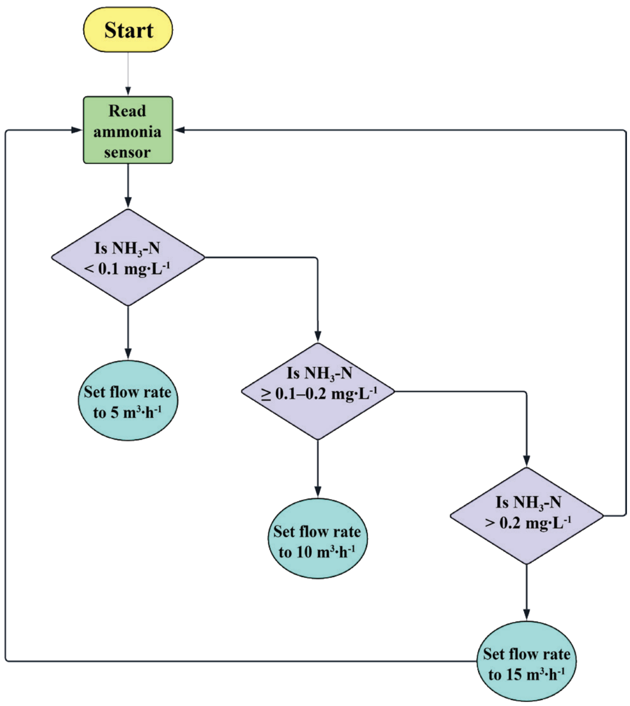

Figure 6. Flowchart of automatic water recirculation rate control logic.

Operation of the i-RAS

i-RAS operation began by filling the system with tap water that had been aerated and left to stand to remove chlorine. Initial water quality parameters, including pH and temperature were checked to ensure optimal conditions before initiating water recirculation. Biological filter system preparation involved collecting sludge containing nitrifying bacteria from an operational MBBR biofilter at the Faculty of Fisheries Technology and Aquatic Resources, Maejo University. This sludge was mixed with water to approximately 10% of the total tank volume, supplemented with glucose (50 mg·L^{-1}) as a carbon source and urea (1 mg·L^{-1}) as a nitrogen source, and was continuously aerated to maintain aerobic conditions. Cultivation continued for 25 days until visible changes in color and turbidity indicated microbial proliferation. Subsequently, the bacterial inoculum was transferred into experimental MBBR biofilters. The system operated without fish, with glucose and urea added at the previous concentrations to simulate fish waste and enhance nitrification processes. NH_3-N, NO_2^--N, and NO_3^--N levels were monitored periodically until NH_3-N and NO_2^--N approached zero, and NO_3^--N accumulated to acceptable levels. Fish were then introduced.

Experimental design

Each i-RAS system was assigned to one of four flow-rate treatments: low recirculation at 0.5 tank volume·h^{-1} (5 m^3·h^{-1}; Treatment 1), medium recirculation at 1.0 tank volume·h^{-1} (10 m^3·h^{-1}; Treatment 2), high recirculation at 1.5 tank volume·h^{-1} (15 m^3·h^{-1}; Treatment 3), and automatic recirculation with a variable flow rate controlled by NH_3-N concentration (Treatment 4).

Fish culture management

Hybrid catfish fingerlings were randomly sampled, counted, and initially weighed to achieve a stocking density of 100 fish·m^{-2}. Fish were fed floating pellet feed containing at least 30% protein (Betagro 382; Betagro Group, Bangkok, Thailand) at 08:00 a.m. and 4:00 p.m. to apparent satiation; fish appetite was monitored and daily feed consumption was recorded. The experimental culture period was 16 weeks.

Growth performance assessment

Every seven days, 20% of fish from each replication were randomly sampled and weighed using a digital scale; total length was also measured. Fish were starved for one day before weighing. Growth and survival parameters were calculated according to Halver (1972), including final weight (FW), weight gain (WG), average total length (ATL), average daily gain (ADG), specific growth rate (SGR), feed conversion ratio (FCR), and survival rate (SR%). The formulas used are as follows:

Weight gain (WG) = (final weight-initial weight)

Average total length (ATL) = mean total length of sampled fish

Average daily gain (ADG) = (final weight-initial weight) / culture period in days

Specific growth rate (SGR) = [ln (final weight)-ln (initial weight)] / culture period in days ×100

Feed conversion ratio (FCR) = (total feed intake / total weight gain)

Survival rate (SR%) = (number of surviving fish / initial number of fish)×100

Water quality monitoring

Water quality was monitored via continuous measurements from installed sensors: NH_3-N was measured using a DSN260 ammonia-nitrogen sensor (Shenzhen Daxsen Technology Co., Ltd., Shenzhen, China); dissolved oxygen (DO) and water temperature were measured using an OPTOD stainless-steel optical DO sensor (Aqualabo, Champagne-sur-Seine, France), and pH was measured using an OEM aquaculture pH sensor (Shenzhen Care Sensor Technology Co., Ltd., Shenzhen, China). Laboratory analyses were conducted every three days and included NH_3-N, NO_2^--N, and NO_3^--N concentrations following Boyd and Tucker (1992). Suspended solids, dissolved oxygen, and biochemical oxygen demand (BOD) were analyzed according to APHA *et al*. (1998). Water samples were collected from three locations: (1) within each of the three culture tanks, (2) the combined wastewater from the three tanks before treatment, and (3) the water exiting the MBBR biofilter before recirculating back into the culture tanks (Figure 7).

Statistical analysis

Results are expressed as mean ± standard deviation (SD). Data were analyzed using one-way analysis of variance (ANOVA). Duncan's multiple range test was applied to determine significant differences between treatments. Significant differences were accepted at $p<0.05$. All statistical analyses were performed using SPSS statistic Base 17.0 for Window EDU S/N 5065845 (SPSS Inc, Chicago, USA).

Animal use approval

The use of animals in this study was approved for scientific purposes under approval number MACUC 026F/2565

RESULTS

Fish growth performance

The growth of hybrid catfish varied significantly across different water recirculation rates after the 16-week culture period (Table 1). Initial fish weights and lengths were not significantly different among treatments ($p>0.05$), indicating uniform initial conditions. After 16 weeks, the automatic recirculation treatment achieved the highest final average weight (308.95±1.43 $g \cdot fish^{-1}$), closely followed by the high recirculation treatment (304.99±3.27 $g \cdot fish^{-1}$). Both treatments had significantly higher final weights compared to medium (281.63±5.23 $g \cdot fish^{-1}$) and low recirculation treatments (269.57±1.17 $g \cdot fish^{-1}$; $p<0.05$).

ADG followed a similar pattern, with the automatic (2.62±0.00 $g \cdot day^{-1}$) and high recirculation (2.58±0.02 $g \cdot day^{-1}$) treatments performing best. No significant difference was observed between these two treatments ($p>0.05$), although both significantly exceeded the medium (2.37±0.04 $g \cdot day^{-1}$) and low (2.27±0.01 $g \cdot day^{-1}$) recirculation treatments ($p<0.05$).

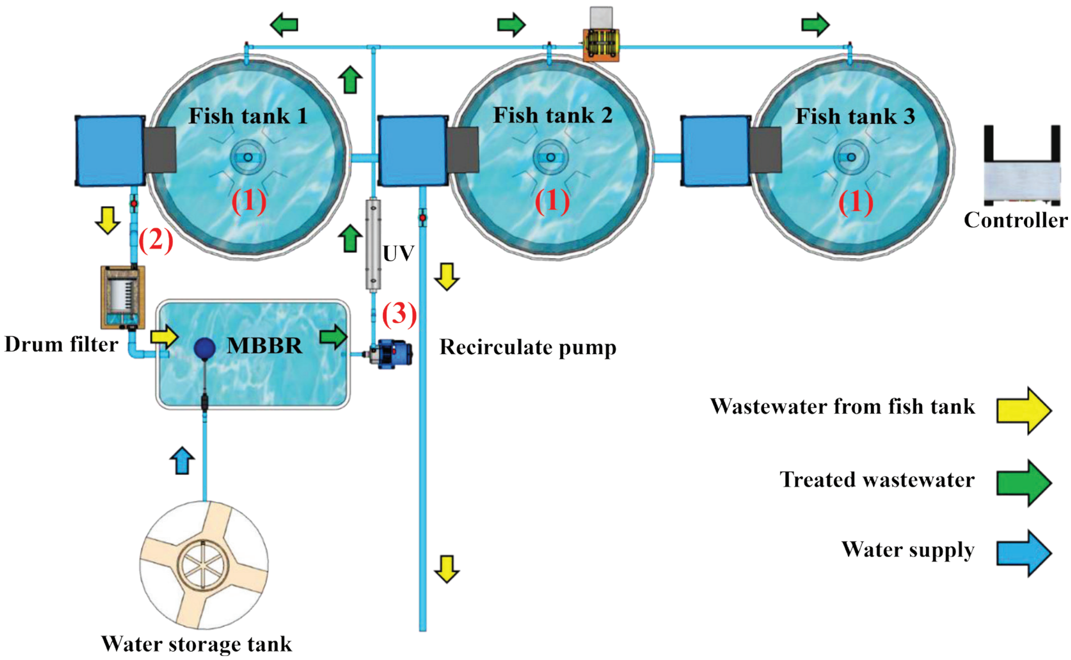

Figure 7. Sampling points for water quality analysis in the RAS.

Table 1. Growth performance of hybrid catfish (*Clarias macrocephalus* × *C. gariepinus*) cultured under different water recirculation regimes in an i-RAS.

Growth performance	Recirculation rate treatments			
	Low rate	Medium rate	High rate	Automatic
Initial weight (g·fish^{-1})	15.65±0.41^{a}	16.39±0.79^{a}	15.99±1.25^{a}	15.75±1.76^{a}
Final weight (g·fish^{-1})	269.57±1.17^{c}	281.63±5.23^{b}	304.99±3.27^{a}	308.95±1.43^{a}
Initial length (cm·fish^{-1})	12.00±0.10^{a}	12.18±0.19^{a}	12.08±0.31^{a}	12.01±0.43^{a}
Final length (cm·fish^{-1})	30.88±0.04^{d}	31.43±0.03^{c}	31.77±0.11^{b}	31.91±0.15^{a}
ADG (g·day^{-1})	2.27±0.01^{c}	2.37±0.04^{b}	2.58±0.02^{a}	2.62±0.00^{a}
Survival rate (%)	78.62±0.08^{c}	85.52±0.46^{b}	90.86±0.29^{a}	90.90±0.46^{a}
Specific growth rate (%)	4.61±0.00^{c}	4.65±0.01^{b}	4.72±0.01^{a}	4.73±0.00^{a}
FCR	1.93±0.06^{c}	1.70±0.05^{b}	1.55±0.04^{a}	1.48±0.01^{a}

Note: Mean±SD (n = 3) in the same row with different superscript letters are significantly different ($p<0.05$).

Survival rate was also significantly affected by the recirculation rates. Fish in the automatic and high recirculation treatments recorded the highest survival percentages (90.90±0.46% and 90.86±0.29%, respectively), significantly exceeding those of fish in the medium (85.52±0.46%) and low (78.62±0.08%) recirculation treatments ($p<0.05$). Specific growth rate (SGR) was highest in the automatic (4.73±0.00%) and high (4.72±0.01%) recirculation treatments, significantly outperforming the medium (4.65±0.01%) and low (4.61±0.00%) treatments ($p<0.05$). FCR was lowest, indicating optimal feed efficiency, in the automatic treatment (1.48±0.01), followed by the high (1.55±0.04), medium (1.70±0.05), and low (1.93±0.06) recirculation treatments ($p<0.05$).

Water quality in fish tanks

Water quality parameters in fish tanks differed significantly among the four treatments (Table 2). Throughout the study period, water temperature remained relatively constant across treatments, ranging from 28.49±0.15 °C to 29.50±0.03 °C. DO concentrations were highest in the high recirculation treatment (4.11±0.04 mg·L^{-1}), followed by medium (3.98±0.05 mg·L^{-1}), automatic (3.95±0.06 mg·L^{-1}), and low (3.84±0.06 mg·L^{-1}) recirculation treatments. The DO concentration in the low recirculation treatment was significantly lower than in the other treatments ($p<0.05$). Significant differences were also observed in pH levels among treatments. The low recirculation treatment showed the highest pH (7.79±0.04), followed by medium (7.52±0.05), automatic (7.30±0.04), and high recirculation treatments (7.09±0.04), with all variations statistically significant ($p<0.05$).

TAN concentrations were highest in the low recirculation treatment (1.34±0.02 mg·L^{-1}) and lowest in the high (0.59±0.02 mg·L^{-1}) and automatic (0.62±0.02 mg·L^{-1}) treatments. Correspondingly, unionized ammonia (NH_3-N) concentrations were significantly elevated in the low recirculation treatment (0.0898±0.0098 mg·L^{-1}). NH_3 concentrations were lowest in the high recirculation treatment (0.0084±0.0008 mg·L^{-1}), followed by automatic (0.0140±0.0016 mg·L^{-1}) and medium (0.0319±0.0050 mg·L^{-1}) treatments, with all differences statistically significant ($p<0.05$). NO_2^--N concentrations trended downwards with increasing recirculation. The highest NO_2^--N level occurred in the low recirculation treatment (0.34±0.00 mg·L^{-1}), whereas the lowest NO_2^--N concentration occurred in the high recirculation treatment (0.06±0.00 mg·L^{-1}), followed by automatic treatment (0.07±0.00 mg·L^{-1}). Similarly, NO_3^--N concentrations were highest in the low recirculation treatment (0.51±0.04 mg·L^{-1}) and lowest in the high (0.27±0.27 mg·L^{-1}) and automatic (0.26±0.26 mg·L^{-1}) treatments, with statistically significant differences ($p<0.05$).

Table 2. Average water quality parameters in fish tanks under different water recirculation rates in the i-RAS.

Average water quality in fish tanks	Recirculation rate treatments			
	Low rate	Medium rate	High rate	Automatic
Temp (°C)	29.50±0.03^{a}	29.04±0.12^{a}	28.49±0.15^{a}	28.81±0.09^{a}
DO (mg·L^{-1})	3.84±0.06^{c}	3.98±0.05^{b}	4.11±0.04^{a}	3.95±0.06^{b}
pH	7.79±0.04^{a}	7.52±0.05^{b}	7.09±0.04^{d}	7.30±0.04^{c}
TAN (mg·L^{-1})	1.34±0.02^{a}	0.87±0.03^{b}	0.59±0.02^{c}	0.62±0.02^{c}
NH_3-N (mg·L^{-1})	0.0898±0.0098^{a}	0.0319±0.0050^{b}	0.0084±0.0008^{c}	0.0140±0.0016^{c}
NO_2^--N (mg·L^{-1})	0.34±0.00^{a}	0.16±0.00^{b}	0.06±0.00^{c}	0.07±0.00^{c}
NO_3^--N (mg·L^{-1})	0.51±0.04^{a}	0.40±0.04^{b}	0.27±0.27^{c}	0.26±0.26^{c}
TSS (mg·L^{-1})	16.89±0.38^{a}	8.45±0.35^{b}	4.48±0.50^{c}	4.50±0.63^{c}
BOD (mg·L^{-1})	4.91±0.10^{a}	3.50±0.12^{b}	2.08±0.09^{c}	2.16±0.09^{c}

Note: Mean±SD (n = 3) in the same row with different superscript letters are significantly different ($p<0.05$).

Total suspended solids (TSS) were significantly lower in the high and automatic treatments, at 4.48±0.50 mg·L^{-1} and 4.50±0.63 mg·L^{-1}, respectively. The low recirculation treatment displayed the highest TSS level (16.89±0.38 mg·L^{-1}). Similarly, BOD was significantly affected by recirculation rates, with the highest value observed in the low recirculation treatment (4.91±0.10 mg·L^{-1}). Conversely, the lowest BOD values were found in the high (2.08±0.09 mg·L^{-1}) and automatic (2.16±0.09 mg·L^{-1}) treatments, indicating superior organic load management in these systems.

Removal performance of i-RAS

The efficiency of the i-RAS in removing key water pollutants varied significantly among different treatments (Table 3). The highest TAN removal efficiency occurred in the automatic recirculation treatment (93.01±0.10%), closely followed by the high recirculation treatment (92.74±0.24%). Both treatments showed significantly greater TAN removal compared to the medium (79.73±0.25%) and low (70.48±0.29%) recirculation treatments ($p<0.05$). The removal efficiency for NH_3-N was similar: automatic recirculation (92.04±0.37%) and high recirculation treatments (90.79±0.41%) exhibited significantly higher NH_3-N removal efficiencies compared to the medium (77.83±0.61%) and low (67.96±0.36%) recirculation treatments ($p<0.05$). NO_2^--N removal efficiency improved significantly with increased recirculation rates. The automatic (93.20±0.22%) and high (92.85±0.25%) recirculation treatments achieved the highest efficiencies, significantly surpassing the medium (79.95±0.75%) and low (69.61±0.97%) treatments ($p<0.05$).

Regarding TSS, the automatic (77.01±0.83%) and high recirculation treatments (74.06±1.27%) demonstrated the highest removal efficiencies, significantly exceeding the medium (51.35±0.09%) and low (34.69±1.40%) treatments ($p<0.05$). BOD removal efficiency also followed this pattern, with the highest removal efficiencies recorded in the automatic (67.90±0.35%) and high (64.91±0.17%) treatments. Both were significantly more effective compared to the medium and particularly the low recirculation treatments, which showed the lowest removal efficiency (30.48±0.12%; $p<0.05$).

Energy consumption of the i-RAS

Total electricity consumption of the i-RAS over the 16-week culture period differed significantly among the four treatments (Figure 8). The highest consumption occurred in the high recirculation treatment (1,026.38±25.90 kWh), which was significantly greater than in the medium (751.18±1.28 kWh) and automatic (761.74±23.07 kWh) treatments. No significant difference was detected between the medium and automatic treatments

($p \geq 0.05$). The lowest energy use was recorded in the low recirculation treatment (505.75±7.77 kWh).

For electricity cost, the high recirculation treatment was the most expensive (121.85±15.4 US$), whereas the medium (89.18±4.94 US$) and automatic (90.43±25.14 US$) treatments showed similar costs, both significantly higher than the low recirculation group (60.04±29.91 US$) ($p<0.05$).

Table 3. System removal efficiencies (%) under different recirculation rates in the i-RAS.

System efficiency	Recirculation rate treatments			
	Low rate	**Medium rate**	**High rate**	**Automatic**
TAN removal efficiency (%)	70.48±0.29[c]	79.73±0.25[b]	92.74±0.24[a]	93.01±0.10[a]
NH_3-N removal efficiency (%)	67.96±0.36[d]	77.83±0.61[c]	90.79±0.41[b]	92.04±0.37[a]
NO_2^--N removal efficiency (%)	69.61±0.97[c]	79.95±0.75[b]	92.85±0.25[a]	93.20±0.22[a]
TSS removal efficiency (%)	34.69±1.40[d]	51.35±0.09[c]	74.06±1.27[b]	77.01±0.83[a]
BOD removal efficiency (%)	30.48±0.12[d]	44.74±0.68[c]	64.91±0.17[b]	67.90±0.35[a]

Note: Mean±SD (n = 3) in the same row with different superscript letters are significantly different ($p<0.05$).

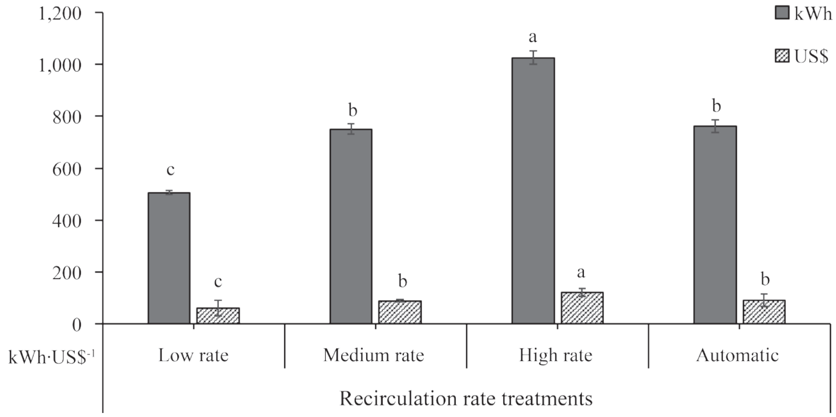

Figure 8. Electricity consumption of the i-RAS under different water recirculation rate treatments over the 16-week culture period. Bars represent mean values, and error bars represent standard deviation (SD). Different letters above the bars denote significant differences among treatment means.

DISCUSSION

This study demonstrates that an intelligent recirculating aquaculture system (i-RAS) equipped with automatic flow control significantly enhances the growth of hybrid catfish and improves water quality compared to systems operating at fixed recirculation rates. Fish reared under the automatic and high recirculation rate treatments exhibited greater growth and higher survival rates than those subjected to medium and low recirculation treatments, indicating the superior environmental conditions afforded by either an increased or dynamically adjusted water exchange. Moreover, the automatic system achieved these benefits while consuming considerably less energy than the high recirculation system, underscoring its operational efficiency.

The primary mechanism underlying these differences among treatments was the effect of recirculation rate on water quality and associated stress responses. In both the automatic and high recirculation treatments, improved water quality was the primary factor driving enhancements in growth and feed efficiency. In the low recirculation treatment, TAN accumulated to 1.34±0.02 mg·L^{-1}, with NH_3-N reaching 0.0898±0.0098 mg·L^{-1}, levels known to impair fish health and growth (Bhatnagar and Devi, 2013). Consequently, fish exposed to the lowest flow-rate experienced chronic stress, leading to reduced growth, poor FCR, and increased mortality. By contrast, the automatic and high recirculation treatments maintained minimal levels of TAN and NO_2^--N, preventing toxicity and ensuring a healthier aquatic environment. Thus, the poor water quality in the low recirculation treatment, characterized by elevated TAN, NO_2^--N, and organic matter, directly accounts for the suboptimal performance observed in that group. Notably, the automatic treatment achieved the lowest FCR, indicating the most efficient feed utilization under optimal water quality conditions.

These results are consistent with previous findings that adequate water exchange enhances fish health and growth by reducing the accumulation of toxic metabolites. Chen *et al*. (2019) showed that higher recirculation rates in shrimp RAS lowered TAN and NO_2^--N and improved growth performance, while insufficient exchange led to deteriorating water quality and increased mortality. Similarly, De León-Ramírez *et al*. (2022) reported that tilapia fingerlings and juveniles achieved optimal growth at moderate to high recirculation rates but suffered stress at lower rates. In our study, the automatic flow-controlled i-RAS maintained water quality and growth comparable to constant high-rate recirculation but with reduced energy use, supporting previous reports by Li *et al*. (2023) and Yang *et al*. (2024) who found that sensor-based or AI-assisted flow and aeration management can optimize water quality and cut energy demand. This agreement may partly reflect the comparable principle of sensor-driven regulation across these systems. However, our approach used a direct ammonia threshold-based control to adjust flow rates, whereas Li *et al*. (2023) employed fuzzy-logic algorithms, and Yang *et al*. (2024) adopted deep-learning-based aeration. These differences highlight that while diverse control strategies can enhance water quality, their efficiency and response dynamics depend on the specific algorithm and sensor integration used.

Beyond technological differences, the biological characteristics of cultured species also play a critical role in determining the optimal recirculation regime. These findings further highlight the importance of maintaining suitable recirculation rates for different species. Higher recirculation rates in RAS are known to mitigate toxic waste accumulation and promote growth in species such as shrimp, although excessive flow rates may induce stress in some species (Chen *et al*., 2019; Zhu *et al*., 2023). In contrast, hybrid catfish in this study tolerated the maximum recirculation rate (1.5 × tank volume·h^{-1}) without any reduction in survival; survival was approximately 90% in both automatic and high-rate treatments, highlighting species-specific differences in flow tolerance. These insights emphasize the need to tailor recirculation strategies not only to system design but also to the physiological and behavioral traits of the cultured species.

Such species-specific differences may arise because hybrid catfish possess higher tolerance to moderate hydrodynamic stress and to elevated TAN compared to more sensitive species such as shrimp or tilapia. Moreover, variations in tank design and water-flow distribution between the i-RAS used in this study and the systems reported by Chen *et al*. (2019) and De León-Ramírez *et al*. (2022) likely influence the optimal recirculation levels required for maintaining fish health. These contextual factors help explain why the hybrid catfish in our system performed well under the maximum flow rate, whereas other species in previous studies experienced stress under similar or even lower flow conditions. Taken together, these considerations provide a useful framework for interpreting the biological responses observed under different recirculation regimes in the present study.

Within this framework, our results clearly demonstrate that insufficient water exchange, as seen in the low-rate treatment (78% survival), compromises fish health. In the low recirculation tanks, hybrid catfish frequently exhibited lethargic swimming near the tank bottom and occasionally gathered in less turbulent areas. Reduced feeding response and intermittent surface gasping were also observed, suggesting early signs of hypoxia or stress. No overt external lesions were recorded, but these behavioral changes, together with elevated TAN and nitrite levels, indicate sublethal physiological stress that likely contributed to reduced survival under low recirculation conditions. Such sublethal stress is typically associated with elevated plasma cortisol and other stress hormones, which increase metabolic energy expenditure while suppressing immune function. This endocrine-mediated trade-off can reduce feed conversion efficiency and compromise disease resistance, ultimately contributing to the observed reduction in growth and survival under low recirculation conditions (Wendelaar Bonga, 1997; Barton, 2002). Such behavioral responses are consistent with previous findings in other fish species, which show reduced spontaneous swimming activity under hypoxia (Domenici *et al*., 2007; 2012) and may display surface gasping or altered escape responses when oxygen is limited. This observation is consistent with De León-Ramírez *et al*. (2022), who reported stress and reduced growth in tilapia at low exchange rates, and with Sühnel *et al*. (2024) who observed improved scallop larval survival under higher exchange rates, reinforcing the necessity of adequate recirculation across aquaculture systems.

A major advantage of the automatic flow control system was its substantial energy savings compared to the fixed high recirculation rate regimen. The high recirculation treatment consumed the most electricity (1,026.38±25.90 kWh) and incurred the highest operational costs. In contrast, the automatic system consumed only 761.74±23.07 kWh, representing an approximate 25% reduction in energy use without compromising water quality or fish growth. By adjusting pump speeds based on real-time NH_3-N levels, the automatic system minimized unnecessary pumping during optimal water quality conditions. This finding validates the sensor-driven variable flow control concept proposed by Chen *et al*. (2021) and aligns with Li *et al*. (2023), who demonstrated the efficacy of fuzzy logic control in maintaining safe TAN levels while enhancing fish growth. The comparable energy-saving outcomes across these studies indicate that the fundamental advantage lies in reducing unnecessary pumping or aeration under favorable water quality conditions. Nonetheless, the degree of savings achieved can differ due to variations in control algorithms, sensor response time, and the farmed species' tolerance thresholds. Additionally, Yang *et al*. (2024) reported comparable outcomes using deep-learning-based aeration strategies, achieving approximately 26.3% energy savings compared to manual systems while maintaining optimal water quality and promoting fish growth. Furthermore, the integration of Internet of Things (IoT) sensors for real-time water quality monitoring has been increasingly recognized as an effective strategy to enhance operational efficiency and resource management in RAS (Flores-Iwasaki *et al*., 2025).

In practical terms, the integration of IoT-based water quality sensors with automated flow control enables continuous real-time monitoring and rapid system response to fluctuations in TAN and dissolved oxygen. Such integration not only improves the accuracy and reliability of the control system but also reduces manual labor requirements and enhances data-driven decision-making for farm managers. Strengthening the IoT framework in intelligent RAS could therefore accelerate adoption in commercial operations and further optimize both production efficiency and resource use. Thus, incorporating advanced automation and intelligent control strategies in recirculating aquaculture systems clearly demonstrates the potential to improve operational efficiency and sustainability, helping to address the common criticism of high energy demands typically associated with RAS (Ahmed and Turchini, 2021).

Despite the promising outcomes, this study has several limitations that warrant consideration when extrapolating the findings. The experiment was conducted with a single species (hybrid catfish), at a fixed stocking density, and within a specific i-RAS configuration. Differences in species' physiology, tolerance to hydrodynamic conditions, and stress responses may influence how other cultured species respond to similar flow control strategies. Likewise, varying stocking densities or alternative system designs could alter water quality dynamics, energy requirements, and the effectiveness of automatic flow regulation. Future studies involving multiple species, a range of stocking densities, and different system architectures would help clarify the broader applicability of these findings. Collectively, these findings underscore that integrating intelligent flow control with consideration of species-specific requirements can enhance production efficiency, fish welfare, and environmental sustainability in RAS.

This study demonstrates the potential of integrating automatic flow control in RAS to improve water quality, enhance fish growth, and reduce energy consumption, thereby contributing to more sustainable aquaculture practices. Beyond these immediate outcomes, scaling such intelligent systems to commercial operations could significantly lower operational costs and improve environmental performance in the aquaculture industry. Future work evaluating these systems commercial conditions and in combination with additional control strategies will be important to guide widespread adoption.

CONCLUSIONS

An intelligent recirculating aquaculture system (i-RAS) equipped with automated flow control was evaluated over a 16-week trial and demonstrated significant improvements in water quality, growth performance, and operational efficiency for hybrid catfish (*Clarias macrocephalus* × *C. gariepinus*) compared to fixed high-rate RAS treatments. By dynamically adjusting recirculation based on real-time NH_3-N levels, the system maintained minimal concentrations of NH_3-N, NO_2^--N, TSS, and BOD, thereby supporting enhanced water quality. Fish reared under automatic control achieved growth, survival, and feed efficiency comparable to those under constant high recirculation rate conditions, but with substantially lower energy consumption. These results highlight that integrating real-time water quality monitoring with responsive flow management in RAS can simultaneously enhance fish welfare, optimize resource use, and promote sustainability, advancing intensive aquaculture toward more energy-efficient and productive practices.

Future research should assess the applicability of automatic flow-controlled i-RAS across diverse cultured species, varying stocking densities, and different system designs, as well as explore integration with predictive sensors and advanced control algorithms to further enhance efficiency. These insights can guide the practical adoption of intelligent RAS in commercial aquaculture operations, helping producers improve resource efficiency, reduce energy costs, and promote more sustainable and resilient farming practices.

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LITERATURE CITED

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

American Public Health Association (APHA). 1998. **Standard Methods for Examination of Water and Wastewater,** 20th ed. American Public Health Association, Washington D.C., USA. 1220 pp.

Barton, B.A. 2002. Stress in fishes: A diversity of responses with particular reference to changes in circulating corticosteroids. **Integrative and Comparative Biology** 42(3): 517–525.

Bhatnagar, A. and P. Devi. 2013. Water quality guidelines for the management of pond fish culture. **International Journal of Environmental Sciences** 3(6): 1980–2009.

Boyd, C.E. and C.S. Tucker. 1992. **Water Quality and Pond Soil Analyses for Aquaculture.** Alabama Agricultural Experiment Station, Auburn University, Alabama, USA. 183 pp.

Chantasarn, A. and O. Lawhavinit. 2018. Status and economic value of hybrid catfish (*Clarias macrocephalus* × *Clarias gariepinus*) farming in Thailand. **Aquaculture Asia** 23(1): 10–18.

Chen, F., Y. Du, T. Qiu, Z. Xu, L. Zhou, J. Xu and M. Sun. 2021. Design of an intelligent variable-flow recirculating aquaculture system based on machine learning methods. **Applied Sciences** 11(14): 6546. DOI: 10.3390/app11146546.

Chen, Z., Z. Chang, L. Zhang, X. Zhu, D. Li and J. Fang. 2019. Effects of water recirculation rate on the microbial community and water quality in relation to the growth and survival of white shrimp (*Litopenaeus vannamei*) in RAS. **BMC Microbiology** 19: 192. DOI: 10.1186/s12866-019-1564-x.

De León-Ramírez, J.J., J.F. García-Trejo, L. Felix-Cuencas, S. López-Tejeida, C.F. Sosa-Ferreyra and A.I. González-Orozco. 2022. Effect of the water exchange rate in a recirculation aquaculture system on growth, glucose and cortisol levels in *Oreochromis niloticus*. **Latin American Journal of Aquatic Research** 50(2): 267–275.

Domenici, P., C.J. Lefrançois and A. Shingles. 2007. Hypoxia and the antipredator behaviours of fishes. **Physiological and Biochemical Zoology** 80(6): 659–669.

Domenici, P., R.S. Svendsen and J.F. Steffensen. 2012. **The effect of hypoxia on fish swimming performance and behaviour.** In: Swimming Physiology of Fish: Toward Using Exercise to Farm a Fit Fish in Sustainable Aquaculture, Fish Physiology Volume 33 (ed. A.P. Farrell), pp. 389–420. Academic Press, San Diego, California, USA.

Flores-Iwasaki, M., G.A. Guadalupe, M. Pachas-Caycho, S. Chapa-Gonza, R.C. Mori-Zabarburú and J.C. Guerrero-Abad. 2025. Internet of Things (IoT) sensors for water quality monitoring in aquaculture systems: A systematic review and bibliometric analysis. **AgriEngineering** 7(3): 78. DOI: 10.3390/agriengineering7030078.

Food and Agriculture Organization of the United Nations (FAO). 2022. **The State of World Fisheries and Aquaculture 2022.** FAO, Rome, Italy. 266 pp.

Halver, J. 1972. **Fish Nutrition.** Academic Press, New York, USA. 726 pp.

Li, H.C., K.W. Yu, C.H. Lien, C. Lin, C.R. Yu and S. Vaidyanathan. 2023. Improving aquaculture water quality using dual-input fuzzy logic control for ammonia nitrogen management. **Journal of Marine Science and Engineering** 11(6): 1109. DOI: 10.3390/jmse11061109.

Martins, C.I., E.H. Eding, M.C. Verdegem, L.T. Heinsbroek, O. Schneider, J.P. Blancheton and J.A. Verreth. 2010. New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. **Aquacultural Engineering** 43(3): 83–93.

Nuaunchun, W., S. Rengpipat and W. Phromkunthong. 2020. Current practices and challenges in hybrid catfish (*Clarias macrocephalus* × *C. gariepinus*) aquaculture in Thailand. **Kasetsart Journal of Animal Sciences** 51(2): 115–124.

Pradeepkiran, J.A. 2019. Aquaculture role in global food security with nutritional value: A review. **Translational Animal Science** 3(2): 903–910.

Sühnel, S., F.J.L. Squella, F.C. da Silva and C.M.R. de Melo. 2024. Water exchange rate and stocking density on the larviculture of the scallop *Nodipecten nodosus* in a recirculation aquaculture system. **Aquaculture** 589: 740922. DOI: 10.1016/j.aquaculture.2024.740922.

Tetreault, J., R.L. Fogle, A. Ramos and M.B. Timmons. 2023. A predictive model of nutrient recovery from RAS drum-screen effluent for reuse in aquaponics. **Horticulturae** 9(3): 403. DOI: 10.3390/horticulturae9030403.

Wendelaar Bonga, S.E. 1997. The stress response in fish. **Physiological Reviews** 77(3): 591–625.

Yang, J., Y. Zhou, Z. Guo, Y. Zhou and Y. Shen. 2024. Deep learning-based intelligent precise aeration strategy for factory recirculating aquaculture systems. **Artificial Intelligence in Agriculture** 12: 57–71.

Zhu, T., R. Yang, R. Xiao, L. Liu, S. Zhu, J. Zhao and Z. Ye. 2023. Effects of flow velocity on the growth performance, antioxidant activity, immunity and intestinal health of Chinese perch (*Siniperca chuatsi*) in recirculating aquaculture systems. **Fish and Shellfish Immunology** 138: 108811. DOI: 10.1016/j.fsi.2023.108811.