Development and on-farm demonstration of a simplified multi-stage biofiltration system for hybrid catfish recirculating aquaculture

Sopawan Rattanaphan[1], Supaporn Noocho[1], Kamonwan Booncharoen[2], Kitikarn Sakuna[1]

[1] Department of Veterinary Science, Faculty of Veterinary Science, Rajamangala University of Technology Srivijaya, Thung Yai, Nakhon Si Thammarat, Thailand;
[2] Department of Bioproduct Technology, Faculty of Science and Technology, Rajamangala University of Technology Srivijaya, Nakhon Si Thammarat, Thailand.
Corresponding author: K. Sakuna, kitikarn.s@rmutsv.ac.th

https://doi.org/10.67784/2007

Abstract. Investment and operational requirements can constrain the adoption of recirculating aquaculture systems (RAS) by small-scale freshwater farmers. This 77-day on-farm evaluation assessed the operational feasibility of a simplified RAS comprising one sedimentation tank, one bioball biofilter, two volcanic-rock biofilters, and a single 75-W pump for hybrid catfish (bighead catfish, *Clarias macrocephalus* Günther, 1864× North African catfish, *Clarias gariepinus* (Burchell, 1822)) production. One 3-m^3 RAS pond and one conventional pond were evaluated under commercial farming conditions. Compared descriptively with the conventional pond, the RAS produced a higher observed final mean body weight (113.40±8.12 vs. 82.60±17.55 g $fish^{-1}$), average daily gain (ADG, 1.29 vs. 0.89 g $fish^{-1}$ day^{-1}), specific growth rate (SGR, 2.71 vs. 2.30% day^{-1}), estimated survival (98.33 vs. 94.17%), and harvested biomass (53.52 vs. 37.35 kg $pond^{-1}$), together with a lower apparent feed conversion ratio (1.19 vs. 1.54). The RAS had higher mean dissolved oxygen (DO) and lower mean chemical oxygen demand (COD). However, ammonia nitrogen and nitrite nitrogen were also higher, indicating that nitrogen conversion did not consistently match the system load. Excluding initial pond filling, the RAS required 74.17% less freshwater and achieved approximately 5.6-fold greater water-use efficiency (1.17 vs. 0.21 kg harvested biomass m^{-3} freshwater). The incremental component investment was 6,800 THB, while the combined freshwater and recirculation-energy cost was lower under the tariffs applied. Because each system was represented by only one pond, the results constitute a descriptive operational comparison rather than statistically replicated evidence of treatment effects. The developed RAS shows practical potential for reducing freshwater demand in hybrid catfish production, but optimization of nitrogen conversion remains necessary. Replicated multi-cycle and multi-farm evaluations are required to confirm its production performance, long-term reliability, and economic feasibility.

Keywords: hybrid catfish, multi-stage biofiltration, on-farm evaluation, recirculating aquaculture system, water-use efficiency.

Introduction. The rapid expansion of aquaculture has intensified the need to increase aquatic food production while improving freshwater-use efficiency and limiting environmental impacts. In 2022, global fisheries and aquaculture production reached a record 223.2 million tonnes, including 130.9 million tonnes from aquaculture. Of the 185.4 million tonnes of aquatic animals produced, aquaculture contributed 94.4 million tonnes and surpassed capture fisheries for the first time (Food and Agriculture Organization, 2024).

Hybrid catfish (bighead catfish, *Clarias macrocephalus* Günther, 1864 × North African catfish, *Clarias gariepinus* (Burchell, 1822)) is among the commercially important freshwater fish cultured in Thailand, particularly by small-scale pond farmers, because of its rapid growth and tolerance of intensive production conditions. However, increasing stocking density and feed input can lead to the accumulation of uneaten feed, fecal material, suspended solids, biodegradable organic matter, and nitrogenous wastes. Inadequate management of these wastes can adversely affect water quality and fish

production performance (Dauda et al., 2019; Gupta et al., 2024). Conventional pond farms commonly manage deteriorating water quality through water replacement, but frequent exchange increases freshwater demand and can discharge water containing organic matter, suspended solids, nitrogen, and phosphorus into the surrounding environment (Dauda et al., 2019).

Recirculating aquaculture systems (RAS) treat and reuse culture water through combinations of solids separation, biological filtration, aeration, and water circulation. These processes can reduce dependence on freshwater replacement and provide greater control over the rearing environment. Recent reviews indicate that RAS performance depends on the integration of system design, solids management, biological treatment, hydraulic operation, monitoring, and energy management (Gupta et al., 2024; Hashmi et al., 2025; Roy et al., 2025).

Biological filtration is particularly important because microorganisms associated with biofilter media mediate the transformation of dissolved nitrogenous wastes. Biofilter performance is influenced not only by the available attachment surface but also by media characteristics, hydraulic conditions, oxygen availability, organic loading, and biofilm development. Previous studies have reported differences in ammonia-removal performance among filter-media types (Cui et al., 2015), while pumice, a porous volcanic material, has been evaluated as a substrate for nitrogen transformation in RAS (Pungrasmi et al., 2016). These findings support the evaluation of porous volcanic rock as a locally obtainable biofilter medium. Nevertheless, the performance of a particular material must be assessed within the hydraulic and operational conditions of the system in which it is used.

Despite their resource-use advantages, the adoption of RAS by small-scale farmers remains constrained by investment requirements, electricity consumption, equipment complexity, and the technical knowledge required for operation and maintenance (Engle, 2023; Gupta et al., 2024; Hashmi et al., 2025). Electricity requirements also vary considerably among RAS configurations because pumping, aeration, oxygenation, filtration, and temperature control contribute differently to total energy demand (Klatt et al., 2026). Simplified systems using fewer energy-consuming components and readily available filtration materials may therefore be more accessible to small-scale producers, provided that they can support acceptable production and water-quality conditions.

Small-scale RAS feasibility has previously been evaluated from technical and economic perspectives (Benjamin et al., 2022), whereas recent reviews have focused more broadly on advances in RAS design, operation, and resource management (Gupta et al., 2024; Hashmi et al., 2025; Roy et al., 2025).

However, field-based information remains limited for simplified RAS operated on commercial farms using locally sourced filtration materials, particularly when production performance, water quality, freshwater input, utility costs, and incremental capital investment are documented within the same production cycle. The present study therefore evaluated a simplified farm-scale RAS incorporating a single low-power pump and commercially available or locally sourced water-treatment components. The purchase costs of the additional recirculation and treatment components were recorded to provide practical investment information; however, no direct economic comparison with alternative RAS configurations was undertaken.

At the community catfish farm in southern Thailand where this study was conducted, replacement of approximately 50% of the pond water per day was an established management practice. The conventional pond retained this routine practice, whereas the developed RAS incorporated sedimentation, bioball filtration, and volcanic-rock filtration to reduce the requirement for freshwater replacement. The objective of this 77-day on-farm demonstration was to document the operational performance of one simplified RAS pond relative to one conventional pond in terms of fish growth, feed-utilization indices, water quality, freshwater input, water-use efficiency, combined freshwater and recirculation-energy costs, and incremental capital investment. Because only one pond represented each production system, the evaluation was intended to provide descriptive operational evidence rather than statistically replicated evidence of treatment effects.

Material and Method

Experimental site. The study was conducted between January and April 2026 at a community-based hybrid catfish (*C. macrocephalus* × *C. gariepinus*) farm in Nakhon Si Thammarat Province, southern Thailand. The experiment was performed under commercial farming conditions to evaluate the practical performance of a simplified RAS designed for small-scale aquaculture production.

Recirculating aquaculture system and water-treatment unit. A simplified RAS was constructed using commercially available and locally sourced materials for hybrid catfish culture under practical farming conditions (Figure 1). The system consisted of one circular culture pond with a working volume of 3 m^3 and a water-treatment unit comprising four tanks connected in series. The treatment unit included one 200-L sedimentation tank, one 200-L biological filtration tank containing 1,000 bioballs (4.5 cm in diameter), and two 150-L biological filtration tanks, each containing 10 kg of volcanic-rock media (particle size: 3-4 cm). The four treatment tanks had a combined nominal volume of 700 L.

Water was continuously circulated using a single 75-W submersible pump with a manufacturer-rated flow rate of 6,000 L h^{-1}. The pump was installed at the bottom center of the culture pond and operated continuously for 24 h day^{-1}. Water was pumped directly from the culture pond into the sedimentation tank and subsequently passed through the bioball filter and the two volcanic-rock filters connected in series.

Within the water-treatment unit, water entered each tank through an inlet pipe extending from the upper side of the tank to near the bottom. Water then flowed upward through each treatment tank and overflowed by gravity into the subsequent tank. In the biological filtration tanks, water flowed upward through the bioball or volcanic-rock media before overflowing into the next treatment stage. The sedimentation tank was used to retain suspended and settleable solids, whereas the bioball and volcanic-rock media provided substrates for microbial attachment and biofilm development. The treatment tanks were installed above the pond water level to permit gravity-driven flow between the treatment stages without additional pumping. After passing through the final volcanic-rock filter, the treated water returned to the culture pond by gravity at a location opposite the pump intake. This arrangement promoted water circulation within the pond and directed suspended solids toward the pump intake for transfer to the sedimentation tank. Freshwater was added as required to compensate for water loss, water removed during routine maintenance, and reductions in the pond water level.

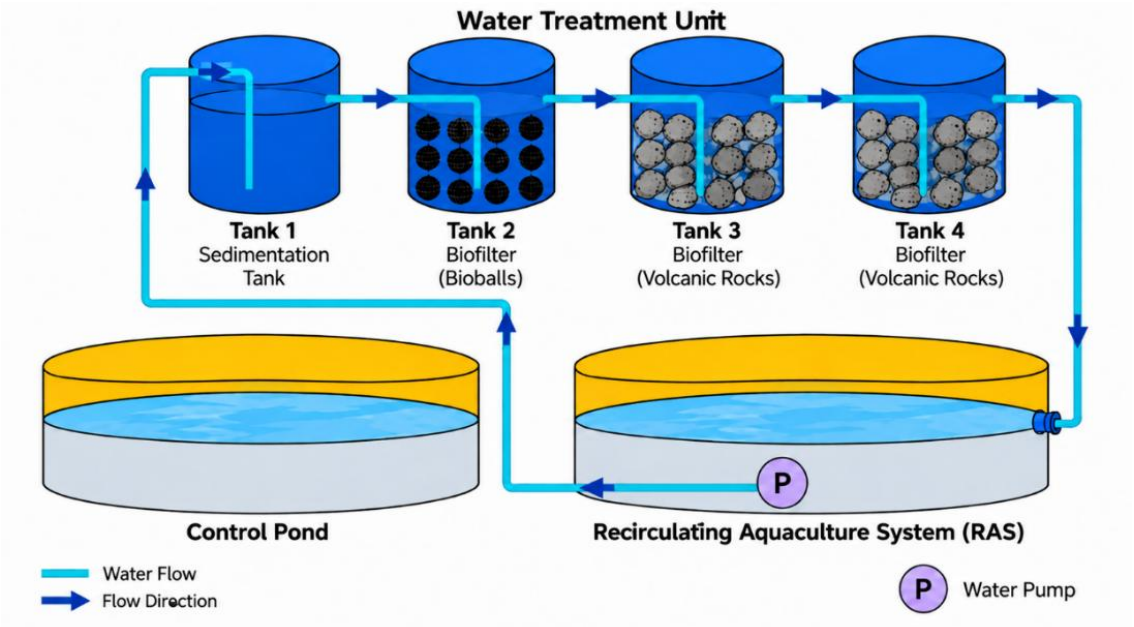

Figure 1 Experimental setup of the recirculating aquaculture system with a four-stage water treatment unit.

Experimental design. The study was conducted as a comparative on-farm demonstration to assess the operational feasibility and production performance of the developed simplified RAS under commercial farming conditions

One conventional pond and one RAS pond, each with a working volume of 3 m^3, were used. Each pond constituted one experimental unit, and each culture system was therefore represented by a single experimental unit without independent pond-level replication. Consequently, the study was designed for descriptive operational comparison rather than inferential statistical testing of differences between treatments.

Each pond was stocked with 480 hybrid catfish (*C. macrocephalus* × *C. gariepinus*), corresponding to a stocking density of 160 fish m^{-3}. Fish had an initial mean body weight of 14.10±5.59 g $fish^{-1}$ and were cultured for 77 days. Fish in both systems were managed according to the routine practices of the collaborating farm, except for water management. The conventional pond was managed using regular freshwater exchange, whereas the RAS operated with continuous water recirculation and limited freshwater replacement. The two systems were evaluated descriptively in terms of growth performance, feed utilization, survival, water quality, freshwater consumption, water-use efficiency, energy consumption, and operating cost.

Fish husbandry. Fish were fed commercial floating pellet diets formulated for catfish (Charoen Pokphand Foods Public Company Limited, Thailand). Three pellet sizes were used during the culture period according to fish size and feeding ability: small, medium, and large pellets with nominal diameters of 2, 3, and 7 mm, respectively. According to the manufacturer-declared guaranteed composition, all three diets contained at least 25% crude protein and 3% crude fat and no more than 8% crude fiber and 12% moisture.

Fish were hand-fed twice daily at 08:00 and 16:00 h to apparent satiation, as judged from their feeding response. Feed was offered gradually until feeding activity markedly declined. The amount of feed offered to each pond was weighed and recorded daily. The amount offered at each feeding was adjusted according to fish appetite and feeding response, whereas pellet size was adjusted according to fish body size and feeding ability throughout the 77-day culture period.

Growth performance. At the beginning of the trial, a total of 48 fish were randomly sampled from the common stock population and individually weighed. Because all fish allocated to the two ponds originated from this population, the mean body weight of the 48 sampled fish was used as the shared initial baseline for the descriptive calculation of growth indices in both ponds. Initial stocked biomass in each pond was estimated as follows:

$$\text{Initial stocked biomass (kg)} = \frac{\text{Shared initial mean body weight (g fish}^{-1}\text{)} \times \text{number of fish stocked}}{1{,}000}$$

At the end of the 77-day culture period, all fish remaining in each pond were harvested. The fish were not counted individually. A random sample of 48 harvested fish from each pond was individually weighed to determine the final mean body weight. All harvested fish, including the sampled individuals, were then collectively weighed to determine the actual final harvested biomass. Because fish were not individually tagged, the fish sampled at the end of the trial were not necessarily the same individuals sampled at the beginning.

Growth performance and feed utilization were evaluated using final mean body weight (FBW), average daily gain (ADG), specific growth rate (SGR), final harvested biomass, biomass gain, apparent feed conversion ratio (aFCR), apparent feed efficiency (FE), and biomass-derived estimated survival. ADG and SGR were calculated as follows:

$$\text{ADG (g fish}^{-1}\text{day}^{-1}\text{)} = \frac{\text{Final mean body weight (g) - Initial mean body weight (g)}}{\text{Culture period (days)}}$$

$$SGR\ (\%\ day^{-1}) = \frac{\ln(\text{Final mean body weight}) - \ln(\text{Initial mean body weight})}{\text{Culture period (days)}} \times 100$$

Biomass gain was calculated as the difference between the actual final harvested biomass and the estimated initial stocked biomass:

Biomass gain (kg) = final harvested biomass (kg) - estimated initial stocked biomass (kg)

Fish were fed to apparent satiation, and the amount of feed offered to each pond was recorded daily. Because uneaten feed and actual feed intake could not be quantified, feed-utilization indices were calculated from the total feed offered and are therefore reported as apparent values:

$$aFCR = \frac{\text{Total feed offered (kg)}}{\text{Biomass gain (kg)}}$$

$$\text{Apparent FE (\%)} = \frac{\text{Biomass gain (kg)}}{\text{Total feed offered (kg)}} \times 100$$

Because the number of fish harvested was not determined by direct counting, the final number of fish and survival were estimated from the actual harvested biomass and the final mean body weight of the 48 sampled fish:

$$\text{Estimated number of fish harvested} = \frac{\text{Final harvested biomass (g)}}{\text{Final mean body weight (g fish}^{-1})}$$

$$\text{Biomass-derived estimated survival (\%)} = \frac{\text{Estimated number of fish harvested}}{\text{Initial number of fish stocked}} \times 100$$

Calculations were performed using unrounded mean body-weight values. The resulting survival estimates assume that the 48 sampled fish adequately represented the body-weight distribution of all harvested fish and that the recorded biomass included all fish harvested from each pond. Accordingly, these values should not be interpreted as survival rates determined by direct enumeration.

Water quality. Water quality was monitored every three days throughout the 77-day culture period, resulting in 26 sampling occasions. Measurements and water sampling were conducted at 07:45 h before the morning feeding to minimize variation associated with sampling time and feeding activity. A fixed sampling point was established 1 m from the edge of each pond at a depth of 15 cm below the water surface.

Water pH was measured *in situ* using a FiveEasy F20 pH meter (Mettler-Toledo GmbH, Greifensee, Switzerland). Water temperature (°C), dissolved oxygen (DO; mg L^{-1}), and total dissolved solids (TDS; mg L^{-1}) were measured *in situ* using a ProQuatro multiparameter meter (YSI Inc., Yellow Springs, OH, USA). The probes were immersed directly in the pond water at the designated sampling point.

Water samples were collected concurrently from the same location and depth for the determination of ammonia nitrogen, nitrite nitrogen, nitrate, chemical oxygen demand (COD), and total Kjeldahl nitrogen (TKN).

Ammonium (NH_4^+) was measured using an HI733 Ammonia High Range Checker® HC colorimeter (Hanna Instruments, Woonsocket, RI, USA). The instrument has a measurement range of 0.0-99.9 mg NH_4^+ L^{-1} and a resolution of 0.1 mg L^{-1}. The measurement is based on an adaptation of the Nessler method. Instrument readings expressed as mg NH_4^+ L^{-1} were converted to ammonia nitrogen (NH_3-N) using the manufacturer-specified conversion factor of 0.776 and were reported as mg N L^{-1}.

Nitrite (NO_2^-) was measured using an HI708 Nitrite High Range Checker® HC colorimeter (Hanna Instruments, Woonsocket, RI, USA). The instrument has a measurement range of 0-150 mg NO_2^- L^{-1}, a resolution of 1 mg L^{-1}. The measurement is

based on an adaptation of the ferrous sulfate colorimetric method. Individual instrument readings, expressed as mg NO_2^- L^{-1}, were converted to nitrite nitrogen (NO_2^--N) by multiplying by the molecular-weight factor 14/46 and were reported as mg N L^{-1}. Readings displayed as zero by the instrument were retained as zero in the descriptive calculations.

Nitrate nitrogen (NO_3^--N) was determined using an HI3874 Nitrate Test Kit (Hanna Instruments, Woonsocket, RI, USA), a visual colorimetric method based on cadmium reduction. A stock nitrate standard containing 100 mg NO_3^- L^{-1} was prepared by dissolving 0.1631 g of analytical-grade potassium nitrate (KNO_3; EMSURE®, Merck, Darmstadt, Germany) in deionized water and diluting to a final volume of 1,000 L. This stock concentration was equivalent to 22.58 mg NO_3^--N L^{-1}. Working standards were prepared from the stock solution and subjected to the same color-development procedure as the water samples. Following color development, the nitrate concentrations were determined by visual comparison using the color-comparison cube supplied with the kit. Because the HI3874 results were expressed directly as NO_3^--N, no molecular-weight conversion factor was applied.

COD (mg L^{-1}) and total Kjeldahl nitrogen (mg N L^{-1}) were determined according to *Standard Methods for the Examination of Water and Wastewater* (American Public Health Association, American Water Works Association, & Water Environment Federation, 2023).

Water consumption and water-use efficiency. The cumulative volume of freshwater added to each culture system during the 77-day culture period was recorded using the farm water meter. Freshwater used for the initial filling of the culture systems was excluded. Water recirculated within the RAS was also not counted as freshwater input. Water-use efficiency (WUE) was expressed as the final harvested fish biomass produced per unit volume of cumulative freshwater input during the culture period:

$$\text{WUE (kg m}^{-3}) = \frac{\text{Final harvested fish biomass (kg)}}{\text{Cumulative freshwater input (m}^3)}$$

Water saving in the RAS relative to the conventional pond was calculated as follows:

$$\text{Water saving (\%)} = \frac{1\text{-}V_{\text{RAS pond}}}{V_{\text{conventional pond}}} \times 100$$

Where:
$V_{\text{RAS pond}}$ and $V_{\text{conventional pond}}$ - the cumulative freshwater inputs, excluding the initial filling volumes, in the RAS and conventional pond, respectively.

Energy consumption and economic evaluation. Electricity consumption of the developed RAS was estimated from the rated power and operating time of the 75-W submersible pump rather than measured directly with an electricity meter. Daily and cycle-level energy consumption were calculated as follows:

$$\text{Daily energy consumption (kWh day}^{-1}) = \text{Pump power (kW)} \times \text{Operating time (h day}^{-1})$$

$$\text{Cycle energy consumption (kWh cycle}^{-1}) = \text{Daily energy consumption (kWh day}^{-1}) \times \text{Culture period (days)}$$

The pump operated continuously for 24 h day^{-1}. Based on its rated power of 0.075 kW, the estimated electricity consumption was 1.80 kWh day^{-1} and 138.60 kWh over the 77-day culture period.

Electricity cost was calculated using a tariff of 3.00 THB kWh^{-1}, whereas freshwater cost was calculated using the local water-supply tariff of 10.50 THB m^{-3}:

$$\text{Electricity cost (THB cycle}^{-1}) = \text{Electricity consumption (kWh cycle}^{-1}) \times 3.00 \text{ THB kWh}^{-1}$$
$$\text{Freshwater cost (THB cycle}^{-1}) = \text{Cumulative freshwater input (m}^3\text{cycle}^{-1}) \times 10.50 \text{ THB m}^{-3}$$

The cumulative freshwater input used in this calculation excluded the initial filling

volume, consistent with the water-consumption assessment. The conventional pond did not use a recirculation pump; therefore, no recirculation-energy cost was assigned to that system. The cost evaluation was limited to freshwater and recirculation-pump electricity. The combined freshwater and recirculation-energy cost was calculated as follows:

$$\text{Combined utility cost (THB cycle}^{-1}\text{)} = \text{Freshwater cost} + \text{Recirculation-energy cost}$$

Feed, labor, maintenance, equipment depreciation, and other costs were not included in this comparison. Capital investment was calculated and reported separately. Incremental capital investment was calculated from the actual purchase costs of the filtration tanks, submersible pump, bioballs, volcanic-rock media, and PVC pipes, valves, and fittings. The culture ponds were excluded because identical 3-m^3 ponds were used in both systems. Therefore, the reported capital investment represented only the additional cost required to convert an existing conventional pond into the developed recirculating configuration.

Statistical analysis. Each pond constituted a single commercial production unit and the pond-level experimental unit for its respective production system. Because the study included only one conventional pond and one RAS pond, independent replication at the pond level was not available, and production-system effects could not be separated from pond-specific effects. Individual fish sampled for body-weight measurements and repeated water-quality observations were therefore regarded as subsamples within their respective production units rather than as independent experimental replicates. Accordingly, the study was treated as an on-farm, field-scale demonstration providing an operational comparison rather than as a replicated experiment designed to test treatment effects.

All data were summarized descriptively. Initial body weight is presented as mean±standard deviation (SD) based on a common random sample of 48 fish collected from the shared stock population before allocation to the two production systems. Final body weight is presented as mean±SD based on a separate random sample of 48 fish collected from each pond at harvest. These SD values describe variation among sampled fish and not variation among independent pond-level experimental units.

For each production system, water-quality data are presented as mean±SD based on 26 sampling occasions during the 77-day culture period. The SD values therefore represent temporal variation within a single pond rather than variation among independently replicated ponds.

Final harvested biomass, biomass gain, ADG, SGR, total feed offered, apparent feed conversion ratio, apparent feed efficiency, biomass-derived estimated survival, cumulative freshwater input, water-use efficiency, estimated energy consumption, utility costs, and capital investment are presented as observed, estimated, or derived operational values, as appropriate. Percentage freshwater saving and fold differences in water-use efficiency were calculated descriptively from the values recorded for the two production units. No inferential statistical tests, confidence intervals for treatment effects, or *p*-values were calculated because each production system was represented by only one pond-level experimental unit.

Ethical statement. This study was reviewed and approved by the Institutional Animal Care and Use Committee (IACUC) of Rajamangala University of Technology Srivijaya, Thailand (Approval No. IAC 05-07-2025), in accordance with the Ethical Principles and Guidelines for the Use of Animals of the National Research Council of Thailand (NRCT). All fish husbandry and sampling procedures were conducted in accordance with the approved animal care and use protocol to minimize animal stress throughout the study.

Results

Growth performance and feed utilization. Growth performance, feed-utilization indices, biomass production, and biomass-derived estimated survival of hybrid catfish cultured in the conventional pond and RAS are presented in Table 1. Before allocation to the two production systems, a common random sample of 48 fish had an initial mean body weight of 14.10±5.59 g fish^{-1}. This shared baseline value was used to estimate the initial stocked biomass and calculate ADG and SGR for both systems. Fish were cultured for 77 days under commercial farming conditions.

At harvest, the RAS showed a higher observed final mean body weight than the conventional pond (113.40±8.12 vs. 82.60±17.55 g fish^{-1}). The corresponding ADG values were 1.29 and 0.89 g fish^{-1} day^{-1}, and the SGR values were 2.71 and 2.30% day^{-1} in the RAS and conventional pond, respectively.

Table 1

Growth performance, feed utilization, biomass production, and survival of hybrid catfish cultured in the conventional pond and recirculating aquaculture system during the 77-day culture period

Parameter	*Conventional pond*	*RAS pond*
Initial mean body weight (g fish^{-1})	14.10±5.59	14.10±5.59
Final mean body weight (g fish^{-1})	82.60±17.55	113.40±8.12
Average daily gain (ADG; g fish^{-1} day^{-1})	0.89	1.29
Specific growth rate (SGR; % day^{-1})	2.30	2.71
Final harvested biomass (kg pond^{-1})	37.35	53.52
Biomass gain (kg pond^{-1})	30.58	46.75
Total feed offered (kg pond^{-1})	47.22	55.78
Apparent feed conversion ratio (aFCR)	1.54	1.19
Apparent feed efficiency (aFE; %)	64.76	83.81
Biomass-derived estimated survival (%)	94.17	98.33

Note: RAS - recirculating aquaculture systems.

Final harvested biomass was 53.52 kg pond^{-1} in the RAS and 37.35 kg pond^{-1} in the conventional pond, corresponding to biomass gains of 46.75 and 30.58 kg pond^{-1}, respectively. Total feed offered during the culture period was 55.78 kg pond^{-1} in the RAS and 47.22 kg pond^{-1} in the conventional pond. Based on the total feed offered, apparent feed efficiency was higher in the RAS than in the conventional pond (83.81 vs. 64.76%), whereas the apparent feed conversion ratio was lower (1.19 vs. 1.54).

Biomass-derived estimated survival was 98.33% in the RAS and 94.17% in the conventional pond. These estimates were based on final harvested biomass and sampled mean body weight rather than direct enumeration of harvested fish. Overall, the RAS showed higher observed or derived values for final mean body weight, ADG, SGR, final harvested biomass, biomass gain, apparent feed efficiency, and estimated survival, together with a lower apparent feed conversion ratio. Because each production system was represented by only one pond-level experimental unit, these findings constitute a descriptive operational comparison and were not subjected to inferential statistical testing.

Water quality. Mean water-quality values recorded during the 77-day culture period are presented in Table 2. Descriptively, the RAS had a higher mean DO concentration than the conventional pond (3.85±2.47 vs. 2.28±1.07 mg L^{-1}) and a lower mean COD (106.23±72.59 vs. 184.50±111.38 mg L^{-1}). Mean water temperature was 26.98±0.93°C in the RAS and 26.85±0.98°C in the conventional pond.

Table 2
Mean water-quality parameters observed in the conventional pond and recirculating aquaculture system during the 77-day culture period

Parameter	*Conventional pond*	*RAS pond*
Water temperature (°C)	26.85±0.98	26.98±0.93
Dissolved oxygen (DO; mg L^{-1})	2.28±1.07	3.85±2.47
pH	6.17±1.11	6.75±0.25
Total dissolved solids (TDS; mg L^{-1})	87.26±27.87	144.23±57.40
Chemical oxygen demand (COD; mg L^{-1})	184.50±111.38	106.23±72.59
Ammonia nitrogen (NH_3-N; mg N L^{-1})	3.08±1.62	4.76±3.10
Nitrite nitrogen (NO_2^--N; mg N L^{-1})	0.01±0.01	0.71±1.04
Nitrate nitrogen (NO_3^--N; mg N L^{-1})	ND	0.93±1.83
Total Kjeldahl nitrogen (TKN; mg N L^{-1})	12.79±8.21	12.27±9.96

Note: ND indicates that no positive nitrate response was observed under the analytical conditions used.

Mean pH was 6.75±0.25 in the RAS and 6.17±1.11 in the conventional pond. Mean TDS concentrations were 144.23±57.40 mg L^{-1} in the RAS and 87.26±27.87 mg L^{-1} in the conventional pond.

Mean ammonia nitrogen concentrations, calculated from the HI733 ammonium readings using the manufacturer-specified conversion factor of 0.776, were 4.76±3.10 mg N L^{-1} in the RAS and 3.08±1.62 mg N L^{-1} in the conventional pond.

Following conversion of the HI708 readings from NO_2^- to NO_2^--N using a molecular-weight factor of 14/46, mean nitrite nitrogen concentrations were 0.71±1.04 mg N L^{-1} in the RAS and 0.01±0.01 mg N L^{-1} in the conventional pond.

Mean nitrate nitrogen (NO_3^--N), determined by visual color comparison using the HI3874 test procedure, was 0.93±1.83 mg N L^{-1} in the RAS, whereas no positive nitrate response was observed in the conventional pond. Mean TKN concentrations were 12.27±9.96 mg N L^{-1} in the RAS and 12.79±8.21 mg N L^{-1} in the conventional pond. Because each production system was represented by a single pond, these temporal observations were used for descriptive comparison only.

Water consumption, energy consumption, and operating costs. Freshwater consumption, estimated energy consumption, operating costs, and water-use-efficiency during the 77-day culture period are summarized in Table 3.

Table 3
Freshwater and energy consumption, operating costs, and water-use efficiency of the conventional pond and recirculating aquaculture system during the 77-day culture period

Parameter	*Conventional pond*	*RAS pond*
Freshwater consumption (m^3 $cycle^{-1}$)	176.63	45.62
Water saving relative to the conventional pond (%)	-	74.17
Freshwater cost (THB $cycle^{-1}$)	1,854.62	479.01
Estimated electricity consumption (kWh $cycle^{-1}$)	0.00	138.60
Estimated electricity cost (THB $cycle^{-1}$)	0.00	415.80
Total operating cost (THB $cycle^{-1}$)	1,854.62	894.81
Operating cost (THB kg^{-1} harvested biomass)	49.66	16.72
Water-use efficiency (kg harvested biomass m^{-3} freshwater)	0.21	1.17

Total freshwater consumption was 45.62 m^3 $cycle^{-1}$ in the RAS and 176.63 m^3 $cycle^{-1}$ in the conventional pond. Thus, the RAS reduced freshwater consumption by 74.17% relative to the conventional pond. Water-use efficiency, calculated as final harvested biomass divided by total freshwater consumption, was 1.17 kg harvested biomass m^{-3} freshwater in the RAS and 0.21 kg harvested biomass m^{-3} freshwater in the conventional pond.

Continuous operation of the 75-W recirculation pump resulted in an estimated electricity consumption of 138.60 kWh $cycle^{-1}$ and an estimated electricity cost of 415.80 THB $cycle^{-1}$ for the RAS. No additional recirculation-pump electricity consumption was assigned to the conventional pond. Freshwater costs were 479.01 THB $cycle^{-1}$ for the RAS

and 1,854.62 THB cycle^{-1} for the conventional pond.

The resulting total operating costs were 894.81 THB cycle^{-1} for the RAS and 1,854.62 THB cycle^{-1} for the conventional pond. When expressed relative to final harvested biomass, the operating cost was 16.72 THB kg^{-1} harvested biomass in the RAS and 49.66 THB kg^{-1} harvested biomass in the conventional pond.

Overall, the developed RAS consumed less freshwater and had lower calculated operating costs both per production cycle and per kilogram of harvested biomass than the conventional pond. These values represent a descriptive comparison between two pond-level production units under the conditions of this on-farm demonstration.

Capital investment. The incremental capital investment required to construct the water-treatment and recirculation components of the developed RAS is presented in Table 4. The total investment was 6,800 THB. Based on the culture-pond working volume of 3 m^3, this corresponded to an incremental capital investment of approximately 2,267 THB m^{-3} of culture volume. The culture pond was excluded from the calculation because identical 3-m^3 ponds were used in both culture systems. Therefore, the reported amount represents the additional investment required to convert an existing conventional pond into the developed recirculating configuration.

Table 4

Incremental capital investment for the recirculation and water-treatment components of the developed RAS

Component	*Specification*	*Quantity*	*Unit cost (THB)*	*Total cost (THB)*
Sedimentation tank	200 L	1 unit	500 unit^{-1}	500
Bioball filtration tank	200 L	1 unit	500 unit^{-1}	500
Volcanic-rock filtration tanks	150 L	2 units	400 unit^{-1}	800
Submersible pump	75 W; rated flow 6,000 L h^{-1}	1 unit	2,000 unit^{-1}	2,000
Bioballs	4.5 cm diameter	1,000 pieces	1 piece^{-1}	1,000
Volcanic rock media	Particle size 3-4 cm	20 kg	50 kg^{-1}	1,000
PVC pipes, valves, and fittings	Complete set	1 set	1,000 set^{-1}	1,000
Total incremental capital investment				6,800
Investment per unit culture volume	Culture volume 3 m^3			2,267 THB m^{-3}

Discussion. Water reuse in RAS can reduce dependence on freshwater, but it also transfers a greater share of waste management to the treatment unit (Badiola et al., 2012; Bergman et al., 2020; Gupta et al., 2024). This trade-off provides the appropriate context for interpreting the present on-farm comparison. The developed system conserved water under commercial operating conditions, while the water-quality pattern indicated that recirculation alone was insufficient to ensure complete control of dissolved nitrogen compounds. Thus, its performance depended not only on water retention but also on the balance among waste production, solids capture, oxygen supply, and biological conversion.

The favorable production pattern observed in the RAS is consistent with the general role of water circulation and treatment in supporting the culture environment (Badiola et al., 2012; Gupta et al., 2024). Adoonsook et al. (2025) reported that sensor-driven variable-flow control in hybrid catfish culture maintained water quality comparable to that under constant high-flow operation while reducing energy consumption and supporting growth and feed conversion. Their findings emphasize that hydraulic control can influence biological performance and energy use simultaneously. Greater oxygen availability and lower organic loading can also support feed intake and growth, whereas oxygen depletion and the microbial decomposition of accumulated wastes can divert energy away from production. Nevertheless, the fixed-flow design used in the present study does not allow the relative contributions of water quality, hydraulic circulation, feeding management, or

initial pond variation to be separated. Feed utilization was also estimated from feed offered rather than feed consumed. The production pattern should therefore be interpreted as a system-level observation rather than evidence that a specific treatment component caused the apparent improvement.

Solids separation before biological filtration is widely recognized as important because retained organic particles exert an oxygen demand and can impair subsequent biofilter performance (Cripps & Bergheim, 2000; Badiola et al., 2012; Gupta et al., 2024). Fernandes et al. (2026) further demonstrated that a high suspended-solids load increased heterotrophic bacterial activity, altered the microbiota of the water and biofilter, impaired nitrification, and reduced fish biomass gain. These findings indicate that inadequate solids removal can affect both biological filtration and production. In the developed system, sedimentation before the three biological filters may have contributed to the observed oxygen and organic-matter profiles by intercepting part of the settleable waste. Continuous circulation may also have improved mixing and oxygen distribution. These mechanisms remain provisional, however, because suspended-solids concentration, stage-specific COD, solids-removal efficiency, and oxygen consumption were not measured. Temporal variability in the water-quality observations further suggests that treatment performance was not constant throughout the production cycle.

The nitrogen profile points to a mismatch between nitrogen loading and biological conversion. The simultaneous occurrence of ammonia nitrogen, nitrite nitrogen, and a nitrate response is compatible with progression along the nitrification pathway, but the accumulation of intermediate compounds indicates that conversion may not have consistently kept pace with waste input. Similar limitations can arise when biofilter capacity or maturity is inadequate, oxygen or pH becomes locally limiting, hydraulic contact is insufficient, or feed and standing biomass increase more rapidly than the active nitrifying community. These factors are central determinants of nitrification in RAS biofilters (Suriasni et al., 2023; Gupta et al., 2024; Jiang et al., 2025).

Bioballs and volcanic rock provide surfaces to which biofilms can attach, but the presence of attachment media does not by itself demonstrate effective nitrification. Pungrasmi et al. (2016), for example, reported nitrogen transformation and removal using pumice, a porous volcanic material, under defined experimental conditions. Biofilm maturity and system management can alter microbial-community structure and nitrification-related activity in RAS biofilters (Rieder et al., 2023; Al Dakdouki et al., 2025; Qi et al., 2025). Fernando et al. (2026) showed that mature nitrifying biofilters resisted invasion by rapidly growing heterotrophic bacteria, whereas perturbation increased invasion success, indicating that biofilter maturity contributes to microbial stability in addition to nitrification. Direct measurements of biofilm development, nitrifier abundance, oxygen within the media, and treatment performance at each filtration stage would therefore be required to determine which component limited conversion in the present system.

The nitrate observations require additional caution. Nitrate was assessed by visual color comparison without instrumental validation, recovery testing, or method-specific detection and quantification limits. The response is therefore best treated as semi-quantitative evidence consistent with nitrogen oxidation, not as proof of complete nitrification or a basis for calculating conversion efficiency. Likewise, comparable TKN concentrations between systems would not establish comparable nitrogen transformation or removal, because TKN combines organic nitrogen and ammonia nitrogen. A mass balance incorporating feed, fish biomass, settled solids, discharged water, and dissolved and particulate nitrogen is needed to distinguish conversion among nitrogen forms from retention or actual removal.

Survival also provides only a limited indication of fish health under these conditions. Total ammonia nitrogen is not equivalent to un-ionized ammonia, the more toxic fraction of which varies strongly with pH and temperature, and fish may experience sublethal effects without mortality. Physiological, immune, metabolic, or histopathological indicators were not examined. Consequently, adjustment of aeration, hydraulic retention time, media maturation, and biofilter capacity should be guided by peak feed and biomass loading and should be verified with both water-quality and fish-health indicators before the design is

applied at higher stocking densities.

The accumulation of TDS is another recognized consequence of intensive water reuse because dissolved substances remain in the system when no specific removal pathway is available (Badiola et al., 2012; Gupta et al., 2024). Without measurements of ionic composition, the sources and biological significance of this accumulation cannot be determined. This observation nevertheless reinforces the need to evaluate water conservation together with the management of retained metabolites and minerals, particularly over longer production cycles in which progressive accumulation may become more pronounced.

The marked reduction in freshwater demand agrees with the central resource-efficiency rationale for recirculating production (Dauda et al., 2019; Bergman et al., 2020; FAO, 2024; Gupta et al., 2024). Its practical importance may be greatest where water supply, pumping, or effluent discharge constrains farm operation. However, the water-use-efficiency estimate reflects both freshwater input and harvested biomass and therefore cannot be attributed to recirculation alone. Moreover, excluding the initial filling volume makes the estimate useful for comparing production-cycle water replacement but not for representing the complete water footprint of the systems.

Economic interpretation likewise depends on the boundary of the calculation. Under the tariffs applied at the study farm, savings in freshwater use offset the estimated electricity requirement for recirculation. This represents a utility-cost comparison rather than evidence of overall profitability. RAS economics can change substantially when feed, labor, maintenance, component replacement, depreciation, financing, water-supply energy, and revenue are included (Pham et al., 2016; Badiola et al., 2018; Bergman et al., 2020; Engle, 2023). Electricity consumption was estimated from rated pump power rather than measured directly, adding further uncertainty. The use of a single pump and readily available media may improve accessibility for small- and medium-scale farms, consistent with interest in simplified catfish RAS designs (Benjamin et al., 2022), but the recorded component outlay cannot establish cost superiority over alternative configurations or long-term economic feasibility.

Interpretation is principally limited by the absence of independent pond-level replication. Repeated measurements within a pond describe temporal or individual variation but do not create independent replicates of the production system; inferential comparisons would therefore risk pseudoreplication. Pond-specific conditions, management differences, or initial variation may have contributed to the observed contrasts. Generalization is further limited by evaluation during a single production cycle at one farm. Replicated trials across cycles, seasons, farms, and stocking densities should quantify hydraulic performance, stage-specific solids and nitrogen removal, biofilter maturation and microbial communities, nitrogen mass balance, sublethal fish responses, metered energy consumption, and full production costs. Such measurements would test the proposed mechanisms and determine whether the operational patterns observed here are reproducible.

Conclusions. This 77-day on-farm evaluation demonstrated the operational feasibility of integrating a sedimentation tank and three biological filtration tanks, operated by a single 75-W pump, into hybrid catfish production. The RAS produced greater harvested biomass and showed more favorable observed growth and apparent feed-utilization indices than the conventional pond. It also maintained higher mean DO and lower mean COD. However, the higher concentrations of ammonia nitrogen, nitrite nitrogen, and TDS indicate that reduced water exchange promoted waste accumulation and that nitrogen conversion did not consistently match the system load. Improving solids removal, aeration, hydraulic operation, and biofilter capacity should therefore be prioritized.

The strongest quantified benefit was freshwater conservation. Excluding the initial filling volume, the RAS required 74.17% less freshwater and achieved approximately 5.6-fold greater water-use efficiency than the conventional pond. Although continuous pump operation consumed an estimated 138.60 kWh per cycle, the combined freshwater and recirculation-energy cost remained lower under the tariffs applied in this study. The incremental component cost was 6,800 THB, or approximately 2,267 THB m^{-3} of culture volume. These figures describe initial investment and selected utility costs only; they do

not establish overall profitability or demonstrate that the system is less expensive than alternative RAS configurations.

Overall, the developed RAS shows practical potential for supporting hybrid catfish production where freshwater availability or water cost constrains farming. Nevertheless, because each system was represented by only one pond, the observed differences are descriptive and cannot be interpreted as definitive treatment effects. Replicated evaluations across multiple production cycles, seasons, farm locations, and stocking densities are required to confirm production performance, optimize nitrogen conversion, assess fish health and long-term system reliability, and determine comprehensive economic feasibility

Acknowledgements. The authors gratefully acknowledge the owner and staff of the participating hybrid catfish farm for providing the study site and assistance with farm operations during the on-farm trial.

Authors Contributions. Conceptualization: SR, KS; Methodology: SR, SN; Formal analysis: SR, KB, KS; Investigation: SR; Data curation: SR; Writing - original draft: SR; Writing - review & editing: SN, KB, KS.

Conflict of Interest. The authors declare that there is no conflict of interest.

Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Funding. This research was financially supported by Rajamangala University of Technology Srivijaya through the University Research Fund (2025) under the research project "Developing a Low-Cost Wastewater Treatment Unit for Catfish Farms Using a Recirculating Aquaculture System (Projects 202913).

References

Adoonsook, D., Boonta, T., & Prasongphol, P. (2025). Automated flow-rate control in intelligent recirculating aquaculture systems (i-RAS) to improve water quality, energy use, and hybrid catfish growth. *Journal of Fisheries and Environment*, *49*(3), 83-98. https://li01.tci-thaijo.org/index.php/JFE/article/view/268079

Al Dakdouki, S., Nivelle, R., Ledoré, Y., Fontaine, P., & Changey, F. (2025). Effects of biofilter management modalities on the microbiological status in RAS water to avoid reducing the capacities of biofilms. *Aquacultural Engineering*, *110*, Article 102522. https://doi.org/10.1016/j.aquaeng.2025.102522

American Public Health Association, American Water Works Association, & Water Environment Federation. (2023). *Standard methods for the examination of water and wastewater* (24th ed.). APHA Press. https://doi.org/10.2105/SMWW.2882.001

Badiola, M., Basurko, O. C., Piedrahita, R., Hundley, P., & Mendiola, D. (2018). Energy use in recirculating aquaculture systems (RAS): a review. *Aquacultural Engineering*, *81*, 57-70. https://doi.org/10.1016/j.aquaeng.2018.03.003

Badiola, M., Mendiola, D., & Bostock, J. (2012). Recirculating aquaculture systems (RAS) analysis: Main issues on management and future challenges. *Aquacultural Engineering*, *51*, 26-35. https://doi.org/10.1016/j.aquaeng.2012.07.004

Benjamin, E. O., Ola, O., & Buchenrieder, G. R. (2022). Feasibility study of a small-scale recirculating aquaculture system for sustainable (peri-)urban farming in Sub-Saharan Africa: A Nigerian perspective. *Land*, *11*(11), Article 2063. https://doi.org/10.3390/land11112063

Bergman, K., Henriksson, P. J. G., Hornborg, S., Troell, M., Borthwick, L., Jonell, M., Philis, G., & Ziegler, F. (2020). Recirculating aquaculture is possible without major energy tradeoff: Life cycle assessment of warmwater fish farming in Sweden. *Environmental Science & Technology*, *54*(24), 16062-16070. https://doi.org/10.1021/acs.est.0c01100

Cripps, S. J., & Bergheim, A. (2000). Solids management and removal for intensive land-based aquaculture production systems. *Aquacultural Engineering*, *22*(1-2), 33-56. https://doi.org/10.1016/S0144-8609(00)00031-5

Cui, Y., Gu, Z., Zheng, X., & Wang, A. (2015). Comparison of five biofilter media in ammonia-removing efficiency in the recirculation aquaculture system. *Journal of Tropical Biology*, *6*(3), 235-241. https://doi.org/10.15886/j.cnki.rdswxb.2015.03.002

Dauda, A. B., Ajadi, A., Tola-Fabunmi, A. S., & Akinwole, A. O. (2019). Waste production in aquaculture: Sources, components and managements in different culture systems. *Aquaculture and Fisheries*, *4*(3), 81-88. https://doi.org/10.1016/j.aaf.2018.10.002

Engle, C. R. (2023). The economics of recirculating aquaculture systems. *Journal of the World Aquaculture Society*, *54*(4), 782-785. https://doi.org/10.1111/jwas.13004

Fernandes, P. M., Fiksdal, L. W. F., Rojas-Tirado, P., Stenhaug, S. R., Khadka, S., Calabrese, S., Powell, M. D., Dahle, H., Bakke, I., Hess-Erga, O.-K., & Fredriksen, S. (2026). Biofilter performance, water quality, and microbial dynamics in RAS operated under high or low suspended solids load. *Aquaculture*, *614*, Article 743559. https://doi.org/10.1016/j.aquaculture.2025.743559

Fernando, F., Khadka, S., Hofstad, K., Fredriksen, S., Vadstein, O., & Bakke, I. (2026). Mature nitrifying biofilters counteract invasion by rapid-growing heterotrophic bacteria in recirculating aquaculture systems (RAS). *Aquaculture*, *620*, Article 743950. https://doi.org/10.1016/j.aquaculture.2026.743950

Food and Agriculture Organization of the United Nations. (2024). *The state of world fisheries and aquaculture 2024: blue transformation in action.* https://doi.org/10.4060/cd0683en

Gupta, S., Makridis, P., Henry, I., Velle-George, M., Ribicic, D., Bhatnagar, A., Skalska-Tuomi, K., Daneshvar, E., Ciani, E., Persson, D., & Netzer, R. (2024). Recent developments in recirculating aquaculture systems: A review. *Aquaculture Research*, *2024*, Article 6096671. https://doi.org/10.1155/are/6096671

Hashmi, Z., Metali, F., Amin, M., Abu Bakar, M. S., Wibisono, Y., Nugroho, W. A., & Bilad, M. R. (2025). Recirculating aquaculture systems: advances, impacts, and integrated pathways for sustainable growth. *Bioresource Technology Reports*, *32*, Article 102340. https://doi.org/10.1016/j.biteb.2025.102340

Jiang, W., Liu, T., Li, S., Li, L., Xu, K., Wang, G., & Guo, E. (2025). The different spatial distribution patterns of nitrifying and denitrifying microbiome in the biofilters of the recirculating aquaculture system. *Microorganisms*, *13*(8), Article 1833. https://doi.org/10.3390/microorganisms13081833

Klatt, L., Pinho, S. M., Mekala, G., Losordo, T. M., & Turchini, G. M. (2026). In search of electricity use patterns for resource-efficient fish farming in recirculating aquaculture systems: a systematic review. *Aquaculture*, *619*, Article 743887. https://doi.org/10.1016/j.aquaculture.2026.743887

Pham, T. A. N., Meuwissen, M. P. M., Le, T. C., Verreth, J. A. J., Bosma, R. H., & Oude Lansink, A. G. J. M. (2016). Economic feasibility of recirculating aquaculture systems in pangasius farming. *Aquaculture Economics & Management*, *20*(2), 185-200. https://doi.org/10.1080/13657305.2016.1156190

Pungrasmi, W., Phinitthanaphak, P., & Powtongsook, S. (2016). Nitrogen removal from a recirculating aquaculture system using a pumice bottom substrate nitrification-denitrification tank. *Ecological Engineering*, *95*, 357-363. https://doi.org/10.1016/j.ecoleng.2016.06.094

Qi, W., Aalto, S. L., Skov, P. V., de Jesus Gregersen, K. J., & Pedersen, L.-F. (2025). Diverse reactions of aquaculture biofilter biofilms following acute high-dose peracetic acid. *Biofilm*, *9*, Article 100277. https://doi.org/10.1016/j.bioflm.2025.100277

Rieder, J., Kapopoulou, A., Bank, C., & Adrian-Kalchhauser, I. (2023). Metagenomics and metabarcoding experimental choices and their impact on microbial community characterization in freshwater recirculating aquaculture systems. *Environmental Microbiome*, *18*, Article 8. https://doi.org/10.1186/s40793-023-00459-z

Roy, S. M., Choi, H., & Kim, T. (2025). Review of state-of-the-art improvements in recirculating aquaculture systems: insights into design, operation, and statistical

modeling approaches. *Aquaculture*, *605*, Article 742545. https://doi.org/10.1016/j.aquaculture.2025.742545
Suriasni, P. A., Faizal, F., Panatarani, C., Hermawan, W., & Joni, I. M. (2023). A review of bubble aeration in biofilter to reduce total ammonia nitrogen of recirculating aquaculture system. *Water*, *15*(4), Article 808. https://doi.org/10.3390/w15040808

Received: 29 June 2026. Accepted: 01 September 2026. Published online: 29 October 2026.
Sopawan Rattanaphan (SR), Department of Veterinary Science, Faculty of Veterinary Science, Rajamangala University of Technology Srivijaya, 133 Moo 5, Thung Yai Subdistrict, Thung Yai District, 80240 Nakhon Si Thammarat, Thailand; e-mail: sopawan.r@rmutsv.ac.th https://orcid.org/0009-0004-4921-0559
Supaporn Noochu (SN), Department of Veterinary Science, Faculty of Veterinary Science, Rajamangala University of Technology Srivijaya, 133 Moo 5, Thung Yai Subdistrict, Thung Yai District, 80240 Nakhon Si Thammarat, Thailand; e-mail: supaporn.h@rmutsv.ac.th https://orcid.org/0009-0003-2283-0689
Kamonwan Booncharoen (KB), Department of Bioproduct Technology, Faculty of Science and Technology, Rajamangala University of Technology Srivijaya, 109 Moo 2, Tham Yai Sub-district, Thung Song District, 80110 Nakhon Si Thammarat, Thailand; e-mail: kamonwan.b@rmutsv.ac.th https://orcid.org/0009-0002-5508-7724
Kitikarn Sakuna (KS), Department of Veterinary Science, Faculty of Veterinary Science, Rajamangala University of Technology Srivijaya, 133 Moo 5, Thung Yai Subdistrict, Thung Yai District, 80240 Nakhon Si Thammarat, Thailand; e-mail: kitikarn.s@rmutsv.ac.th https://orcid.org/0009-0006-8674-1935
This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.
How to cite this article:
Rattanaphan, S., Noochu, S., Booncharoen, K., & Sakuna, K. (2026). Development and on-farm demonstration of a simplified multi-stage biofiltration system for hybrid catfish recirculating aquaculture. *Aquaculture, Aquarium, Conservation & Legislation*, *19*(5), 2551-2565. https://doi.org/10.67784/2007