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Performance Evaluation of Water Change and Filtration in Recirculating Aquaculture Systems for Improving Water, Energy, and Cost Efficiency in Grass Carp

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Abstract: The growing demand for efficient, water-conserving, and sustainable aquaculture systems has accelerated the development of recirculating aquaculture system (RAS) technology. Although RAS can reduce water use by 90–99% compared to conventional systems, challenges remain related to metabolic waste accumulation and energy requirements. Therefore, this study aims to: (1) evaluate the effects of water change (25% and 50%) and filtration on water quality and water use; (2) assess system performance based on energy consumption and operational costs; and (3) determine the most efficient configuration for grass carp (Ctenopharyngodon idella) culture. The study was conducted at the Terpadu Laboratory, IPB Dramaga Campus, Bogor, using a completely randomized design (CRD) with three treatments: 25% water change (WC25), 50% water change (WC50), and a filtration system without water change (FS). Water changes were applied when water quality parameters exceeded predefined thresholds. Water quality parameters (ammonia, nitrite, nitrate, temperature, dissolved oxygen, and pH) were monitored daily, while water use, energy consumption, and operational costs were recorded and analyzed. The filtration system (FS) was the most effective in maintaining water quality, reducing ammonia from 2.25 mg/L to 0.25 mg/L, nitrite from 0.15 mg/L to 0.01 mg/L, and nitrate from 80 mg/L to 25 mg/L. FS also demonstrated the highest water use efficiency, consuming only 5 m³/month with a water cost of IDR 30,055. Although energy consumption was slightly higher, FS resulted in the lowest total operational cost (IDR 969,667/month). The integration of a filtration system in RAS is more effective in maintaining water quality, reducing water consumption, and improving economic efficiency compared to water change strategies, making it a suitable approach for sustainable grass carp aquaculture.

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Keywords: filtration; grass carp; operating costs; water quality; water change

1. Introduction

Aquaculture has experienced significant expansion to meet the increasing global demand for food, particularly in Asia, which accounts for more than 90% of global aquaculture production [1]. In Indonesia, total fishery production reached 24,737,618.25 tons in 2023, with 16,967,518.25 tons contributed by aquaculture activities [2]. Despite this rapid growth, the sustainability of aquaculture systems remains a major concern, particularly due to inefficiencies in water and energy use [3].

Recirculating aquaculture systems (RAS) have been developed to address water-use inefficiency by recycling 90–99% of water, significantly reducing freshwater demand compared to conventional systems [4].

However, maintaining water quality within RAS is essential for ensuring system stability and fish health. Key parameters, including temperature, pH, dissolved oxygen,
ammonia, nitrite, and nitrate, must be carefully controlled, as their imbalance can negatively affect production performance. Furthermore, although RAS offers substantial water savings, its implementation is often constrained by high initial investment and increased energy requirements [5].

Water change is commonly applied as a water quality management strategy and is defined as the replacement of a portion of culture water with fresh water at a specified percentage [6]. Previous studies have shown that systems relying on frequent water change require higher water inputs, whereas the integration of filtration systems can significantly reduce water demand. Nevertheless, improved filtration performance is often associated with increased energy consumption, indicating a trade-off between water efficiency and operational costs [7,8].

Research has demonstrated that varying water change strategies influence the survival and growth of barramundi larvae (Lates calcarifer). Specifically, water changes of 20%, 25%, and 30% were investigated, with a 20% change producing the most favorable outcomes in terms of survival rate and growth performance [6]. Moreover, research indicates that water change strategies significantly affect the growth and survival of rainbow fish. Specifically, daily variations in water change of 0%, 50%, 100%, and 150% were examined, with a 100% daily water change demonstrating the most favorable outcomes in terms of specific growth rate (SGR) and survival rate (SR) [9]. Nonetheless, there is a paucity of research investigating the effects of reduced water change rates (e.g., 25%) and the concurrent implementation of water change and filtration systems.

Grass carp (Ctenopharyngodon idella) were selected for this study owing to their rapid growth, high adaptability, and herbivorous feeding behavior, which enhance feed efficiency and reduce production costs [10]. This study aimed to (1) evaluate the effects of water changes (25% and 50%) and filtration on water quality parameters, including temperature, dissolved oxygen, pH, ammonia, nitrite, and nitrate, as well as water use; (2) assess the performance of these strategies in a recirculating aquaculture system (RAS) in terms of energy consumption and operational costs to identify the most efficient configuration; and (3) examine the technical and operational feasibility of these approaches to support sustainable grass carp aquaculture.

2. Methods

2.1. Location and Materials

This study was conducted at the Terpadu Laboratory, IPB University, on the Dramaga Campus in Bogor. The experimental design used a recirculating aquaculture system (RAS) with grass carp (Ctenopharyngodon idella) as the test species. The fish had an average length of 5 ± 0.4 cm and weight of 2 ± 0.1 g. The study used stationery, a digital balance, caliper, sample containers, a pH meter, a DO meter, and a Tetra test kit for ammonia, nitrite, and nitrate levels. A laptop with SPSS, Origin, Word, Excel, AutoCAD, and SketchUp was also used. The materials included clean water for RAS, recirculated water samples for quality analysis, and reagents for the Tetra test kit.

2.2. Research Procedure

2.2.1. Experimental Setup

Conditioning the recirculating aquaculture system (RAS) was the initial phase to ensure optimal functionality. Water meters at the inlet and outlet quantified water usage. Sixteen tanks were filled with 185 L of clean municipal water. Grass carp were stocked at a density of 20 fish per tank, or one fish per 9.25 L. The fish were fed commercial feed (Primafeed, 35% protein) at 5% of their body weight, twice daily at 09:00 and 15:00. During acclimatization, the system operated without interventions to help fish adapt to the new environment.

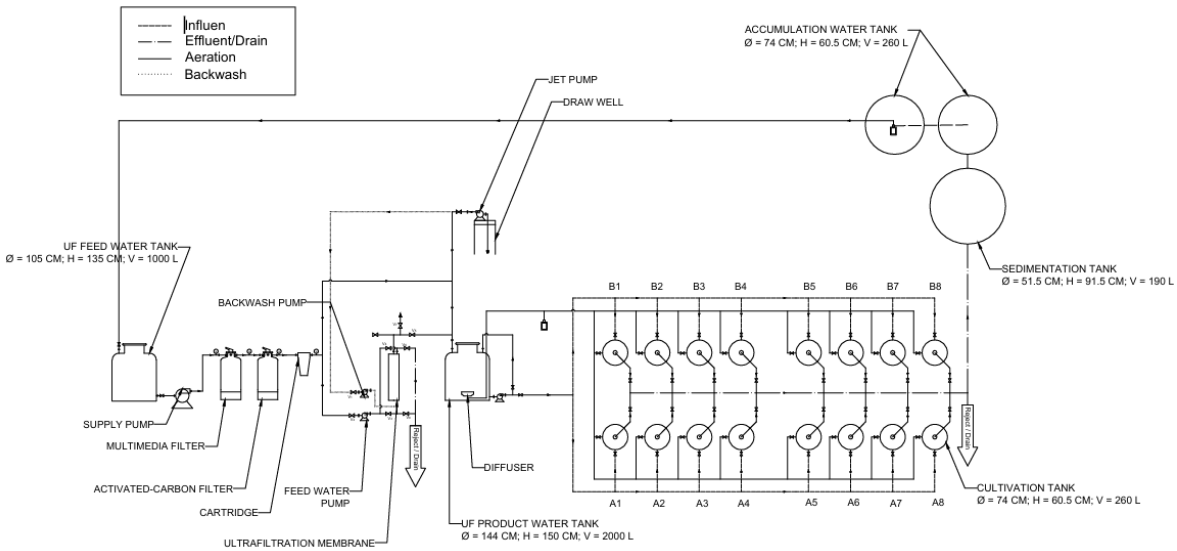


Figure 1. Process and instrumentation of the recirculating aquaculture system (RAS)

2.2.2. *Experimental Procedure and Data Collection*

The study utilized a completely randomized design (CRD) encompassing three treatments: a 25% water change (WC25), a 50% water change (WC50), and a filtration system without water change (FS). The experiment was initiated when the concentrations of ammonia (NH_3), nitrite (NO_2^-), and nitrate (NO_3^-) exceeded predefined thresholds. Water changes were not conducted on a predetermined schedule but were triggered when these parameters surpassed the thresholds. When the thresholds were exceeded, 25% or 50% of the total system volume was discharged and immediately replenished with fresh water, after which monitoring continued until the thresholds were exceeded once again. Water quality parameters, including temperature, pH, dissolved oxygen, ammonia, nitrite, and nitrate, were monitored daily at 15:00 h in each of the 16 tanks, with one water sample collected per tank per observation, resulting in 16 samples per day. The total number of samples collected was contingent upon the duration of the experiment. The concentrations of NH_3, NO_2^-, and NO_3^- were measured using a Tetra test kit. Water usage was calculated based on the volumes of water discharged and replenished.

Treatments WC25 and WC50 involved partial water changes of 25% (1.1 m³) and 50% (2.2 m³) of the total system volume (4.4 m³), respectively. Treatment FS employed a closed-loop filtration system incorporating multimedia filters, activated carbon, cartridge filters, and an ultrafiltration membrane (SRUF-4040) without routine water changes. Water quality was monitored until the parameters exceeded the predefined thresholds or stabilized according to established standards. Water loss due to evaporation and the energy consumption of the pump (0.125 kW) and filtration system were recorded to evaluate water use, energy consumption, and operational costs.

2.2.3. *Data Processing and Statistical Analysis*

Data processing and analysis were conducted utilizing both primary and secondary data sources. Water demand was determined based on system volume, water change volume, change frequency, and water loss, as shown in **Equation 1**. Energy consumption was evaluated based on pump power and operational duration, as shown in **Equation 2**. Operational costs were derived from water, electricity, and feed components, with the total

operational cost calculated using **Equation 3**. Water quality data were analyzed using the Kruskal–Wallis test, followed by the Mann–Whitney test when significant differences were detected ($p<0.05$).

$$\mathrm{KAT} = (\mathrm{V_{system}} \times \mathrm{N}) + (\frac{\mathrm{V_{replace}}}{\mathrm{F}} \times \mathrm{T}) \quad (1)$$

where,

KAT = total water requirement (liters/month)
N = number of system refills during the period
V_{ganti} = volume of water replaced per change (liters)
F = frequency of water change (days)
T = total days in the period

$$\mathrm{C_{electricity}} = \mathrm{P_{pump}} \times \mathrm{t} \times \mathrm{T_{pump}} \quad (2)$$

where,

$C_{electricity}$= electricity costs incurred (IDR)
P_{pump} = pump power (kW)
t = operating time (hours)
$T_{electricity}$ = electricity rate per kWh (IDR/kWh)

$$\mathrm{Cost_{operational}} = \mathrm{C_{water}} + \mathrm{C_{electricity}} + \mathrm{C_{feed}} \quad (3)$$

where,

C_{water} = water cost (IDR)
$C_{electricity}$ = electricity cost (IDR)
C_{feed} = feed cost (IDR)

3. Result and Discussion

3.1. Controlled Recirculating Aquaqulture System (RAS)

In a controlled recirculating aquaculture system (RAS), water is continuously treated through a series of filtration processes to maintain optimal conditions for fish culture. As shown in **Figure 1**, the system begins with water being conveyed from the source to the UF raw water tank, followed by distribution to 16 rearing tanks arranged in two rows (A and B). From the rearing tanks, the flow is directed to a sedimentation tank, then to an accumulation tank, before being pumped to the ultrafiltration (UF) feed tank. It subsequently passes through a series of filtration units, including multimedia, activated carbon, cartridge filters, and an ultrafiltration membrane (SRUF-4040), prior to being recirculated within the system.

To maintain stable system performance, the RAS was equipped with aeration and automated control units. Each rearing tank was fitted with a diffuser connected to a ring blower to enhance dissolved oxygen (DO) levels and improve gas exchange efficiency, while the product water tank utilized a larger diffuser for broader oxygen distribution [11,12]. Water flow was regulated using individual valves to ensure uniform distribution, with a total flow rate of 40 L/min (2.5 L/min per tank), monitored using a water meter [13]. In addition, water levels were automatically controlled using a level control switch to ensure continuous operation. This integrated configuration facilitates the removal of suspended solids, organic compounds, and microorganisms, thereby maintaining stable water quality within the system [14].

3.2. Water Quality

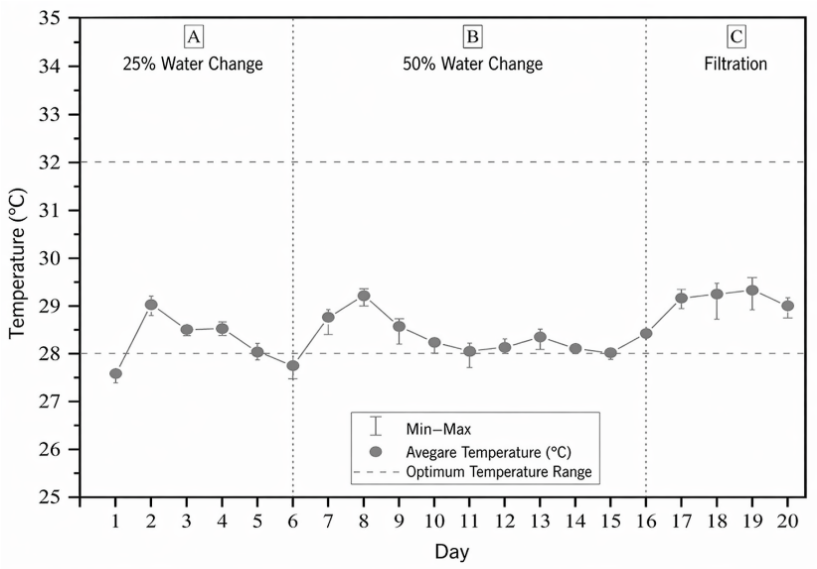


Figure 2. Results of measurements for temperature

Water quality parameters, including temperature, dissolved oxygen (DO), and pH, were monitored over 20 days in 16 rearing tanks under three treatments: 25% water change, 50% water change, and a filtration system. Temperature dynamics presented in **Figure 2** indicate a range of 27.6 to 29.3 °C, with an average of 28.6 °C. The highest value was observed under the filtration treatment, likely due to heat generated by recirculation and pump operation. This range is consistent with optimal thermal conditions for freshwater aquaculture (28–32 °C) and supports stable physiological performance [15].

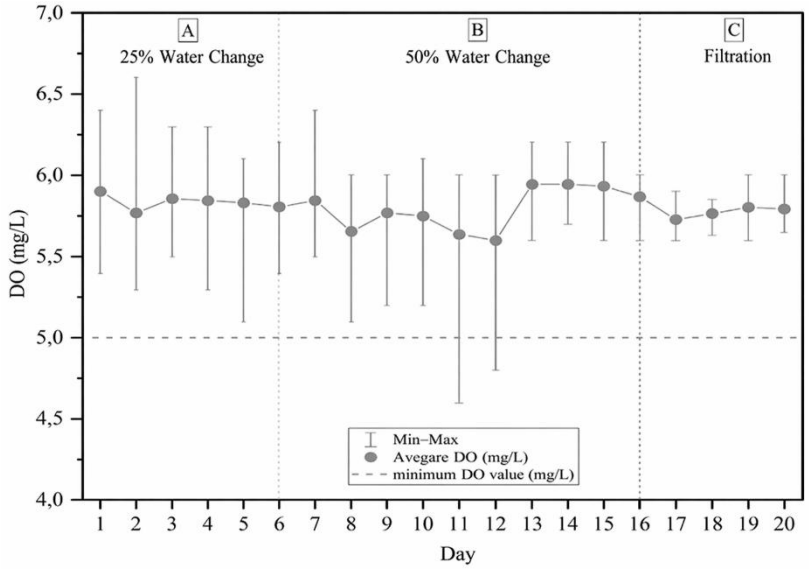


Figure 3. Results of measurements for DO

Dissolved oxygen profiles in **Figure *3*** demonstrate stable concentrations throughout the experiment, ranging from 5.6 to 5.9 mg/L, with an average of 5.8 mg/L. These values lie within the recommended range for freshwater aquaculture (5–8 mg/L) [16], indicating that the aeration system consistently maintained adequate oxygen availability across all treatments.

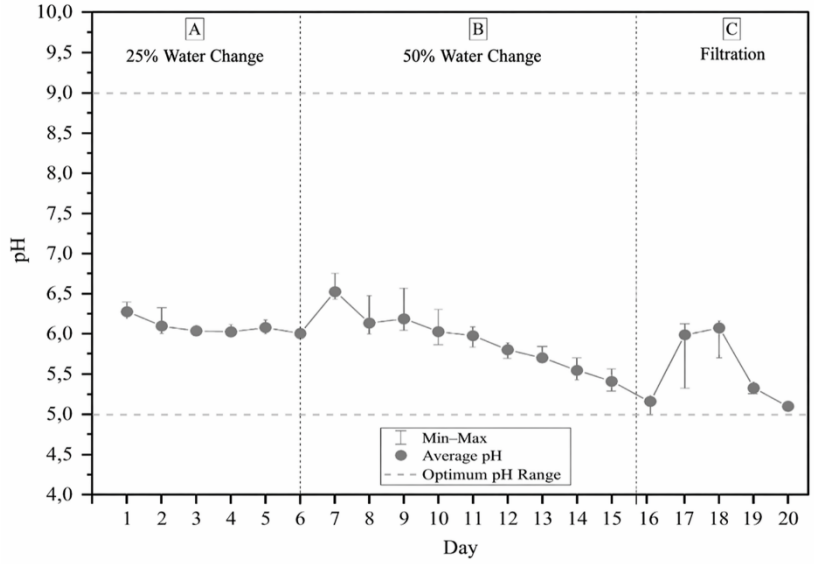


Figure 4. Results of measurements for pH

The pH trend shown in **Figure *4*** reflects a gradual decrease from 6.5 to 5.1, with an average of 5.9. This reduction is likely associated with nitrification processes and the accumulation of organic matter. Although still within the acceptable range for aquaculture systems (pH 5.0–9.0), the values tend toward the lower limit of the optimal range (6–8), which may influence physiological performance under prolonged exposure [17].

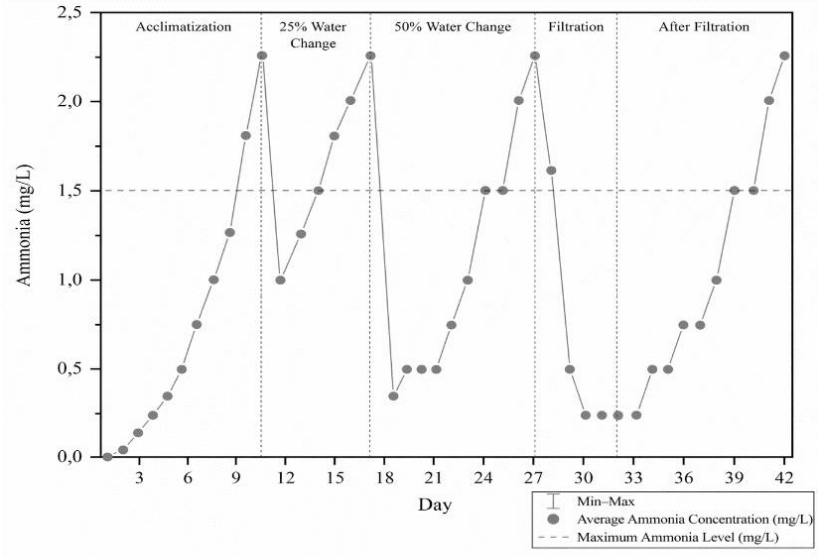


Figure 5. Results of measurements for Ammonia

Ammonia accumulation during acclimatization, as illustrated in **Figure 5**, reaching 2.25 mg/L by day 11 and exceeding the recommended threshold for freshwater aquaculture (1.0–1.5 mg/L) [18]. A 25% water change reduced ammonia to 1.00 mg/L; however, the concentration returned to 2.25 mg/L within six days. A 50% water change further reduced ammonia to 0.03 mg/L, but levels increased again within ten days. In contrast, the filtration system reduced ammonia from 2.25 mg/L to 0.25 mg/L within three days and maintained concentrations below the threshold during operation. Following the cessation of filtration, ammonia increased again to 2.25 mg/L within 11 days,

demonstrating that filtration provides more effective and sustained control of ammonia accumulation than periodic water change.

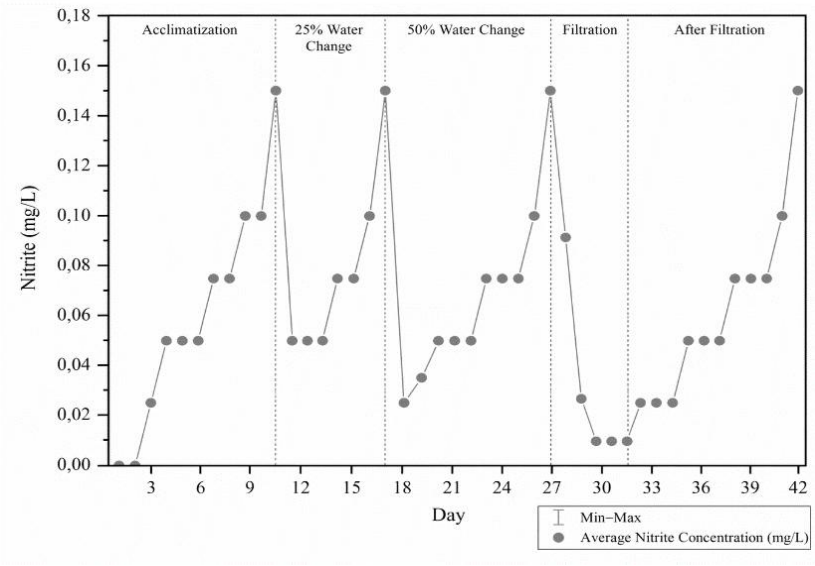


Figure 6. Results of measurements for Nitrite

Nitrite concentration exhibited a similar trend, as presented in **Figure 6**, increasing to 0.15 mg/L during acclimatization. Water changes of 25% and 50% reduced nitrite concentrations to 0.05 mg/L and 0.03 mg/L, respectively; however, levels increased again after 6 and 10 days. The filtration system reduced nitrite from 0.15 mg/L to 0.01 mg/L within three days and maintained stable concentrations during operation. After filtration was discontinued, nitrite gradually increased to 0.15 mg/L within 11 days. Although nitrite concentrations remained within the acceptable range for aquaculture systems (0–0.5 mg/L) and below the chronic toxicity threshold (>0.2 mg/L) [19], the observed pattern confirms that water change alone provides limited long-term control compared to filtration.

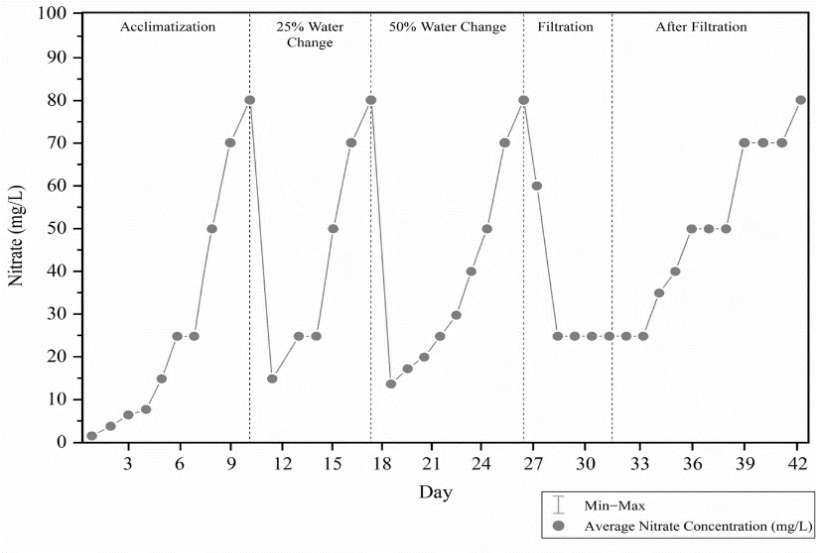


Figure 7. Results of measurements for Nitrate

Nitrate concentration increased during acclimatization, as presented in **Figure 7**, reaching 80 mg/L. Water changes of 25% and 50% reduced nitrate concentrations to 15 mg/L and 12.5 mg/L, respectively; however, levels returned to 80 mg/L after 6 and 10 days. The filtration system reduced nitrate from 80 mg/L to 25 mg/L within two days and maintained stable concentrations during operation. In the absence of filtration, nitrate levels increased again to 80 mg/L within 11 days. Although nitrate concentrations remained below the acceptable limit for aquaculture systems (<100 mg/L) [20], this trend demonstrates that water change alone is insufficient for long-term nitrate control, whereas filtration ensures greater stability.

Table 1. Results of statistical analyses using the Kruskal-Wallis and Mann-Whitney tests

Parameter	Results of the Statistical Analysis for Each Treatment			
	Kruskal-Wallis	Mann-Whitney		
		A	B	C
Temperature	<0.001	28.24±0.07a	28.39±0.09b	29.20±0.17c
pH	<0.001	6.08±0.04a	5.85±0.05b	5.63±0.07c
DO	0.294	5.84±0.19a	5.80±0.13a	5.77±0.07a
Ammonia	0.074	1.62±0.46a	1.08±0.68a	0.64±0.63a
Nitrite	0.128	0.08±0.037a	0.07±0.035a	0.03±0.038a
Nitrate	0.786	44.16±26.72a	36.05±23.65a	33.75±17.5a

Note: a,b,c: The identical letter notation signifies no statistically significant difference ($p>0.05$) as determined by the Mann-Whitney test at a 95% confidence interval.

Statistical results presented in **Table *1*** indicate significant differences in temperature and pH among treatments ($p < 0.05$), while DO showed no significant variation ($p > 0.05$), confirming consistent oxygen conditions across treatments. Although ammonia, nitrite, and nitrate did not differ significantly ($p > 0.05$), a consistent decreasing trend from water change treatments to the filtration system was observed, indicating improved performance of filtration in controlling nitrogen accumulation.

3.3. Water Consumption

Efficient water use is a critical aspect of aquaculture management, particularly in recirculating aquaculture systems (RAS) designed to minimize resource consumption. Water usage and associated costs for each treatment are presented in **Table 2**.

Table 2. Monthly Analysis of Water Consumption and Associated Costs for Each Treatment

Component	Treatment		
	WC25	WC50	FS
Frequency of Water Changes per Month (times)	5	3	0
System Volume (m^3)	4.4	4.4	4.4
Volume of Water per Change (m^3)	1.1	2.2	0
Total Water Changed per Month (m^3)	5.5	6.6	0
Water Loss per Month (m^3)	0.029	0.030	0.037
Water Utilized for Backwash (m^3)	0	0	0.6
Total Water Utilized (m^3)	10	11	5
Water Price (Rp)	59,429.00	68,000.00	30,055.00

Note: WC25 = 25% water change; WC50 = 50% water change; FS = filtration system without water change.

Table 2 indicates that the filtration system achieved the highest water use efficiency among all treatments. The system consumed 5 m^3 per month, including 0.037 m^3 attributed to evaporation and

0.6 m³ required for backwashing processes. In contrast, the 25% and 50% water change treatments required substantially higher water inputs, totaling 10 m³ and 11 m³ per month, respectively, due to repeated water replacement, evaporation losses, and operational requirements.These differences in water consumption directly influenced operational costs. The filtration system incurred a monthly water cost of IDR 30,055, which was significantly lower than the costs associated with the 25% (IDR 59,429) and 50% (IDR 68,000) water change treatments. This demonstrates that the integration of filtration within RAS substantially reduces water demand and associated costs while maintaining system performance.

3.4. Energy Consumption

Energy efficiency plays a critical role in aquaculture system performance, particularly in recirculating aquaculture systems (RAS) that depend on continuous operation of pumps and aeration units. Energy consumption and associated costs for each treatment are summarized in **Table 3**.

Table 3. Monthly Analysis of Energy Consumption and Associated Costs for Each Treatment

Component	Treatment		
	WC25	**WC50**	**FS**
Surface Pump (kWh)	90	90	90
Submersible Pump (kWh)	72	72	72
Filtration Pump (kWh)	0	0	13.5
Aerator (kWh)	324	324	324
Total Electricity Consumption (kWh)	486	486	499.5
Electricity Price (Rp)	811,392.00	811,392.00	833,930.00

Note: WC25 = 25% water change; WC50 = 50% water change; FS = filtration system without water change.

As presented in **Table *3***, aeration accounted for the largest share of total energy consumption, operating continuously for 24 hours and contributing 324 kWh per month (66.7% of total energy use). The surface and submersible pumps, which were operated across all treatments, consumed 90 kWh and 72 kWh per month, respectively. The filtration treatment required additional energy due to the operation of two extra pumps, increasing total consumption by 13.5 kWh to 499.5 kWh per month, slightly higher than that of the 25% and 50% water change treatments. This increase in energy consumption resulted in higher electricity costs for the filtration system, reaching IDR 833,939 per month, compared to IDR 811,392 for the water change treatments. Despite the higher energy demand, the filtration system provided improved water quality control, indicating a trade-off between energy consumption and system performance.

3.5. Operating Costs

Operational cost efficiency is crucial in high-density aquaculture systems, such as recirculating aquaculture systems (RAS). In this study, total operational costs comprised water, electricity, and feed. Variations in water and electricity costs among treatments were driven by differences in water quality management strategies, whereas feed costs remained comparable due to uniform stocking density and feeding regimes, as summarized in **Table 4**.

Table 4. Summary of Monthly Operational Costs for Each Treatment

Cost Component	Treatment		
	WC25	WC50	FS
Water Cost (Rp)	59,429.00	68,000.00	30,055.00
Electricity Cost (Rp)	811,392.00	811,392.00	833,930.00
Feed Cost (Rp)	105,681.00	105,681.00	105,681.00
Total Cost (Rp)	976,502.00	985,073.00	969,667.00

Note: WC25 = 25% water change; WC50 = 50% water change; FS = filtration system without water change.

Table 4 indicates that the filtration system resulted in the lowest total operational cost, amounting to IDR 969,667 per month. Although this treatment required additional energy for pump operation, the reduction in water consumption significantly lowered overall expenses. The water cost under the filtration system was IDR 30,055 per month, substantially lower than those of the 25% and 50% water change treatments, which reached IDR 59,429 and IDR 68,000, respectively. Feed costs were consistent across all treatments, with a monthly consumption of 4.8 kg corresponding to IDR 105,681. These findings demonstrate that the filtration-based RAS provides greater resource efficiency and cost-effectiveness than water change strategies.

4. Conclusion

This study evaluated the effects of water change (25% and 50%) and filtration within a recirculating aquaculture system (RAS) on water quality, water consumption, energy use, and operational costs in grass carp culture. The results show that the filtration system provided more stable control of nitrogen compounds, reducing ammonia from 2.25 mg/L to 0.25 mg/L, nitrite from 0.15 mg/L to 0.01 mg/L, and nitrate from 80 mg/L to 25 mg/L, whereas water change treatments resulted in only temporary improvements. In terms of resource efficiency, the filtration system reduced water consumption to 5 m^3 per month, compared to 10–11 m^3 in water change treatments, with a corresponding water cost of IDR 30,055. Although energy consumption increased slightly to 499.5 kWh per month due to additional pumps, the total operational cost was lower (IDR 969,667) than that of the water change treatments. Overall, filtration-based RAS offers a more effective and resource-efficient strategy than water change alone for maintaining water quality and reducing operational costs. These findings highlight the potential of filtration systems to improve the sustainability and economic performance of freshwater aquaculture. Further research is recommended to evaluate long-term system performance and environmental impacts, including energy optimization and carbon emissions.

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