SUSTAINABLE AQUACULTURE AND AQUATIC SCIENCE

Volume-1

Editors:
Dr. Muhammad Yamin
Dr. Rasidi
Lolita Thesiana, S.Si., M.T.

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(Volume – 1)

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Dr. Muhammad Yamin
Senior Researcher, National Research and Innovation Agency Republic of Indonesia

Dr. Rasidi
Senior Researcher, National Research and Innovation Agency Republic of Indonesia

Lolita Thesiana, S.Si., M.T.
Senior Researcher, National Research and Innovation Agency Republic of Indonesia

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Delhi, 110086, India

Preface

A book of Sustainable Aquaculture and Aquatic Sciences, Volume 1. Recirculating Aquaculture System aims to connect scientific knowledge with practical innovation, providing a multidisciplinary viewpoint that encompasses biology, ecology, engineering, socioeconomics and policy in aquaculture. It examines design, innovation technology, feed strategy and efficiency, water additive, disease control, the role of microbiome, case study on fish and shrimp, social economy and policy correlated with RAS.

The discussion of RAS design, feed management techniques and microbial ecology, essential RAS components, begins the book. Next, we are going to discuss how RAS may help with sustainable shrimp, fish and ornamental fish farming, as well as novel innovations and performance criteria that are specific to each species. The business prospects and social and economic factors that support RAS technology implementation are also explored. Relevance across academic and professional fields is ensured by the content, which reflects both theoretical knowledge and applied experience. This effort aims to enhance the global dialogue on sustainable aquatic food production by using the experience of researchers, practitioners and policymakers. We aspire that the insights presented will stimulate innovation, promote responsible practices and enhance collaborative endeavors to ensure that aquaculture and aquatic sciences progress in alignment with the planet's ecological limits, delivering nutritious food now, without jeopardizing the requirements of future generations.

All of whose insights have strengthened this publication have our warmest appreciation, as do the organizations and individuals that work to promote sustainable aquaculture practices.

Bogor-Indonesia, September 2025

Authors

Dedication

This book is dedicated to all the hardworking people who are interested in RAS. This book aims to be an essential source for everyone interested in RAS technology and its potential uses in various aquaculture contexts, whether they be students, researchers, professionals or policymakers. It is also dedicated to the researchers and scientists who actively investigate methods to enhance recirculating aquaculture systems, improving sustainability, productivity and resilience. Their innovations facilitate a more hopeful future in aquaculture.

This book is a significant resource and source of motivation for anyone who is dedicated to the advancement of RAS farming and research. Overall, we work to cultivate a more beneficial and sustainable industry with great appreciation and respect.

Acknowledgments

Every chapter of this book would not have been possible without the generous support and help provided by the National Research and Innovation Agency, Republic of Indonesia. Furthermore, we would like to express our appreciation to our colleagues, who helped us out tremendously by offering extra insights that were critical in making this book what it is today.

Competing Interests

The authors of this book declare that they have no financial or other interests that could be considered a conflict of interest. Everyone who helped with the research or wrote the parts did it sincerely and no personal, financial or business connections affected the final product.

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CHAPTER

Evaluation of Biofilter Implementation in Recirculating Aquaculture Systems: Types, Mechanisms and Design

Kukuh Adiyana
Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia

Eddy Supriyono
Department of Aquaculture, Faculty of Fisheries and Marine Sciences, IPB University, West Java, Indonesia

Lolita Thesiana*
Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia

Tuti Wahyuni
Research Center for Agroindustry, National Research and Innovation Agency (BRIN), Indonesia

***Corresponding Author:** loli002@brin.go.id

Abstract

Recirculating Aquaculture System (RAS) is a closed fish farming system that relies on biofilters to maintain water quality through nitrification. The effectiveness of biofilters in oxidizing nitrogenous waste, such as ammonia, into nitrate is highly influenced by factors including biofilter design, type and environmental conditions such as temperature, pH and dissolved oxygen concentration. Commonly used biofilters include fixed media filters, moving bed bioreactors (MBBR), trickling filters and fluidized bed filters. MBBR has been demonstrated to exhibit high nitrogen removal efficiency, whereas trickling filters enhance nitrification through improved oxygen exposure. Fluidized bed filters offer high nitrification capacity but require a more complex flow regulation system. Optimal biofilter design in RAS considers ammonia waste load, the surface area of the filtration media and the hydraulic loading rate (HLR) of the filter. Applying a trickling filter in *Panulirus sp.* lobster aquaculture has reduced Total Ammonia Nitrogen (TAN) by up to 23.33 g TAN/m^3/day. At the same time, the use of a submerged biofilter in *Litopenaeus vannamei* shrimp culture effectively maintains water quality

without liquid waste disposal (zero wastewater discharge). By optimizing biofiltration systems, RAS technology can enhance fish productivity while contributing to the sustainability of environmentally friendly aquaculture.

Keywords: RAS, biofilter, design, trickle filter, fixed media filter, Moving bed bioreactor.

Introduction

The Recirculating Aquaculture System represents a closed loop fish culture method that utilizes biological biofiltration mechanisms to uphold optimal water quality by nitrification. During nitrification, autotrophic nitrifying bacteria form biofilms on filter media and play a crucial role in oxidizing toxic nitrogenous waste into less harmful compounds. Ammonia (NH_3/NH_4^+), a metabolic excretion product of fish, is first oxidized by ammonia-oxidizing bacteria (AOB) such as Nitrosomonas sp. into nitrite (NO_2^-), which is then further oxidized by nitrite-oxidizing bacteria (NOB) such as Nitrobacter sp. into nitrate (NO_3^-) [1, 2]. This sequential aerobic nitrification reduces the accumulation of toxic ammonia and nitrite in the water, thereby maintaining a suitable environment for fish growth. The efficiency of biofilter performance is significantly influenced by environmental factors such as temperature, pH and dissolved oxygen concentration [3-5].

Given the pivotal function of biofiltration in preserving water quality through nitrification, consideration must also be oriented toward the selection and configuration of biofilters to guarantee optimal system efficacy. The success of Recirculating Aquaculture Systems (RAS) is profoundly reliant on the selection of suitable biofilter design and classification, considering operational mechanisms and efficiency. Various biofilter types have been implemented in RAS, including moving bed biofilters, submerged biofilters and fluidized bed biofilters, each with distinct advantages and challenges. For instance, moving bed biofilters are known for their ability to enhance the surface area available for nitrifying bacterial colonies through continuously moving media, allowing for more bacterial attachment and growth [6, 7]. Furthermore, it increases efficiency in nitrification by maximizing the contact between contaminated water and the filter media, which is covered with a biofilm.

In contrast, submerged biofilters have a simpler design and operation but may face limitations in oxygen transfer, which can reduce nitrification effectiveness [8, 9]. Meanwhile, fluidized bed biofilters utilize high flow velocities to keep media in suspension, thereby maximizing surface area and biofilm development. However, they require more complex flow regulation and oxygen distribution management [10, 11]. These operational considerations highlight the importance of carefully optimizing biofilter design parameters to ensure biological efficiency and system stability.

Optimal biofilter design in RAS must consider various technical factors that influence its efficiency, such as filter media selection, the ratio of surface area to media volume and hydraulic loading rate (HLR). Media with larger surface areas support denser biofilm growth, enhancing the biofilter's ability to oxidize ammonia into nitrate [12]. Furthermore, a suitable Hydraulic Loading Rate (HLR) guarantees optimal water movement through the filtration system, permitting adequate duration for nitrifying microorganisms to execute maximal conversion [13]. An additional vital consideration encompasses maintenance protocols such as backwashing, which aids in the elimination of amassed particulates and preserves optimal water circulation. Regular maintenance ensures sustained biofilter performance over time, preventing clogging or reduced nitrification capacity [8, 9].

When selecting a biofilter, considerations include its design, operational mechanism, hydraulic retention time (HRT) and practical factors such as ease of maintenance and associated costs. The appropriate biofilter selection enables the optimization of RAS technology to improve water quality, support fish health and ensure sustainable, environmentally friendly and efficient aquaculture operations.

Types and Applications of Biofilters

In Recirculating Aquaculture Systems, the biofilter plays a crucial role, acting as the heart of the entire system. The biofilter is responsible for converting dissolved nitrogenous wastes, primarily ammonia (NH_3) and nitrite (NO_2^-), which are toxic to fish, into nitrate (NO_3^-), a less toxic substance for aquatic organisms, through the process of biological nitrification. The successful operation of an RAS is highly dependent on the efficiency and stability of the biofilter. The commonly used types of biofilters include fixed media filters, Moving Bed Bioreactors (MBBR), trickling filters and fluidized bed filters.

Fixed Media Filters

Within Recirculating Aquaculture Systems, fixed media filters are water treatment units primarily for ammonia conversion. This conversion process is crucial for maintaining optimal water quality conducive to aquaculture activities. The design of these filters is predicated on the mass balance of the organic load from the system's effluent, which dictates specific media dimensions and characteristics. Submerged filter media, characterized by a large specific surface area, facilitate a compact design and can effectively reduce the water's total ammonia nitrogen (TAN) levels, promoting sustainable aquaculture practices [14]. To better understand their operational characteristics and limitations, exploring the different types and practical applications of fixed media filters in RAS settings is essential.

Types and applications of biofilters fixed media filters utilize solid, stationary media (e.g., gravel, plastic bio-balls or crushed shells) as a substrate for the attachment of nitrifying bacterial biofilms [15]. Water flows through the gaps between the media, allowing bacteria such as *Nitrosomonas* sp. and *Nitrobacter* sp. to oxidize ammonia into nitrite and nitrate. This design is simple; however, the accumulation of solids and excessive biofilm growth, particularly under high organic loads, can clog the media pores, reducing dissolved oxygen levels [8, 9]. A variation of this system, known as a submerged filter, consists of media that remain completely immersed in water. To further assess the practical implications of biofilter design, recent studies have compared different bioreactor configurations to evaluate their performance in real world aquaculture settings.

A study has been done to evaluate the impact of three different bioreactor configurations within a recirculating aquaculture system on the growth and health of rainbow trout (*Oncorhynchus mykiss*), water quality and nitrification efficiency [16]. These configurations were two fixed-bed bioreactors (FBBR) in series (FF), one FBBR followed by one moving bed bioreactor (MBBR) (FM) and two MBBR in series (MM). In this study, the fixed-bed bioreactors (FBBR) were designed to trap fine particulate solids and were susceptible to clogging, thus requiring regular backwashing. Conversely, the moving bed bioreactors (MBBR) utilized continuously moving carrier media, creating a scouring effect that sheared off solid particles and excess biomass, which were subsequently removed from the system by a solids removal unit; MBBR typically do not require backwashing [16]. This study found that the bioreactor design did not significantly affect fish growth performance, as measured by a specific growth rate (SGR) between 1.59 and 1.64% /day and a feed conversion ratio (FCR) between 0.95 and 0.98. Furthermore, no significant histopathological differences were observed in the gills, kidneys, liver and heart tissues among the RAS treatment groups and a flow through control group. However, significant differences were observed in water quality [16].

Regarding nitrite parameters recorded during the study, nitrite concentrations were significantly higher in the FF system than in the FM and MM systems. However, the treatments did not affect the mean total ammonia nitrogen (TAN) concentration. Nitrification rates, measured in the laboratory, corresponded with the in-water nitrite levels, indicating the highest total ammonium oxidation rate in the MM system. Within the FF group, the second FBBR exhibited a lower nitrification rate than the first FBBR. In contrast, nitrification rates were consistent across all MBBR, suggesting that MBBR are more stable and reliable for nitrification [16].

Concentrations of total organic carbon (TOC) and UV254 absorbance, indicative of organic matter accumulation, were higher in the groups with moving bed systems (FM and MM) compared to the FF group. The highest CO_2 concentration was observed in the FF group, while it was lower in the FM and MM groups, likely due to the continuous aeration within the MBBR. Regarding solids, the total solids removed from the entire RAS unit (swirl separator and drum filter) were similar among treatments. However, the removal of solids by the drum filter was significantly influenced by the bioreactor system, with the drum filter in the MM system removing the most solids, followed by FM and the least in FF. These findings showed that although MBBR releases more fine solids into the circulating water, the 60 μm drum filter can compensate for this accumulation. The total volume of particles in the biologically filtered water was higher in the MM group compared to the FF group [16].

In conclusion, although the bioreactor configuration did not significantly affect the growth and health of rainbow trout in this study, the bioreactor design influenced water quality, primarily through impacts on solids accumulation and nitrification efficiency. The FF system tended to accumulate nitrite, whereas the FM and MM systems were prone to increase organic content and fine particles, which were managed mainly by the drum filter [16]. This study also found that, in terms of nitrification efficiency, fixed media filters performed worse than Moving Bed Bioreactors due to uneven water flow, which reduced the effectiveness of the surface area for nitrification and led to nitrite accumulation.

Extending this discussion to shrimp aquaculture, to study the use of aerated submerged filters with bioblock media in *Litopenaeus vannamei* post-larvae rearing [17], resulted in stable water quality that met the required standards throughout the cultivation period. The submerged filter treatment using green tanks achieved the highest biomass production (928 g/m^3) and survival rate (SR) of almost 73%.

Moving Bed Bioreactor

The Moving Bed Bioreactor (MBBR) is a biofilm-based water treatment technology in which microorganisms attach to freely moving carriers within a reactor filled with wastewater. This system combines the advantages of activated sludge and fixed film biofilters, leading to high efficiency in nitrogen and organic compound removal in aquaculture wastewater [6, 7]. One of its main advantages is its high efficiency in ammonia and nitrate removal. Studies indicate that MBBR can achieve nitrification efficiency exceeding 92%, maintaining ammonia concentrations below 0.5 mg/L, thereby significantly improving water quality for aquaculture [6, 18].

Building on the demonstrated efficiency of MBBR in nitrogen removal, recent studies have explored its integration into shrimp culture systems to enhance water quality and animal performance. A pilot-scale study was conducted to compare the capabilities of *Litopenaeus vannamei* culture systems using Biofloc Technology (BFT) and Advanced Biofloc Technology (ABFT) combined with a Moving Bed Bioreactor (MBBR) in terms of enhancing shrimp growth performance and their ability to regulate ammonia, nitrite and nitrate concentrations in the water [19]. The BFT culture tank had a capacity of 250 m^3 with a larval shrimp density of 125,000 individuals per tank (initial weight 7 mg/shrimp) and was maintained for 100 days. The ABFT system used in the study had the same culture tank capacity and larval shrimp density as the BFT system but was equipped with 4 MBBR units utilizing K5 media (occupying 35% of the biofilter tank volume). The results from this pilot-scale research indicated that the combination of MBBR with a biofloc system in *L. vannamei* shrimp culture produced optimal water quality, with TAN and nitrite removal rates of 65.86% and 57.51%, respectively. This treatment resulted in the highest SGR (7.81%/ day) and SR (81.22%) [19].

Trickling filters

Trickling filters use media that are not fully submerged, providing a large surface area for biofilm growth. These media are typically highly porous, allowing bacterial colonization and nutrient processing. Trickling filters are effective in nutrient removal, with efficiency dependent on filtration rates. In aquaculture applications, this system is commonly modified using sponge-based media, known as Downflow Hanging Sponge (DHS) reactors [20]. DHS reactors offer low operational costs, as they do not require external aeration to supply dissolved oxygen, making them highly energy-efficient [21, 22]. Another advantage is their adaptability to seawater conditions, as DHS reactors have been shown to maintain nitrification efficiency even in high salinity environments [23]. A separate study also demonstrated that DHS reactors successfully reduced Total Ammonia Nitrogen (TAN) concentrations from 10 mg/L to 1 mg/L within 11 days, proving their effectiveness in mitigating ammonia toxicity [22].

Additionally, a study was conducted to determine the performance of a trickling filter concerning different feed types and feeding strategies in the aquaculture of Gilthead Sea bream (*Sparus aurata*) within a Recirculating Aquaculture System (RAS) [24]. The RAS in this research featured a 250 m^3 fish culture tank, equipped with a sponge-based solid removal unit (cleaned weekly) and a 0.025 m^3 trickling filter with bactoballs as media, a heating unit and a system water flow rate of 1.08 m^3/hour. The treatments in this study involved different feed types: a commercial pellet feed as control, a fish meal-based meal feed and a plant-based meal feed, as well as various feeding strategies (manual feeding, automatic feeder and auto demand feeder/*ad libitum*) with a feeding frequency of three times a day (Monday-Friday), once on Saturday and no feeding on Sunday. The fish density in each culture tank was 30 individuals with an average initial weight of 7.9 grams/fish and they were cultured for 140 days. The results of this research indicated that the use of trickling filters in the Gilthead Sea bream (*Sparus aurata*) culture, where fish meal-based feeding resulted in the highest TAN removal rate of 0.11 ± 0.01 gN-TAN/m^2 biofiltration per day. This approach yielded optimal production performance, with an SGR of 2.05%/day and an SR of 88.3%. Furthermore, when viewed from the perspective of the feeding strategy treatment, the auto demand feeder/ad libitum produced the best ammonia removal performance in the trickling filter, achieving 0.10 gN-TAN removed per m^2 biofiltration area per day [24].

Fluidized bed filters

Fluidized bed filters employ fine granular media (typically sand) that are fluidized by upward water flow, keeping the media in suspension and allowing continuous movement within the reactor column. Each sand particle is coated with nitrifying biofilm and remains in motion, maximizing contact between water, nutrients, oxygen and biofilm. Fluidized sand biofilters can sustain higher nitrification loads due to their large specific surface area (5000–20,000 m^2/m^3), which particularly suitable for high-density aquaculture systems with substantial feed inputs [10]. Another advantage of this system is the low cost and wide availability of sand as a filtration medium. However, fluidized bed filters require continuous pumping energy to maintain fluidization and are highly sensitive to organic load fluctuations. Excessive organic matter can cause biofilm aggregation, leading to oxygen depletion and filter instability [11]. The Cyclobio Fluidized Sand Filter, when supplemented with daily NH_4Cl dosing in *Ictalurus sp.* aquaculture, demonstrated TAN removal efficiency of 51.4%, achieving a Volumetric TAN Removal Rate (VTR) of 93.2 g TAN/m^3 media per day. This filtration capacity was sufficient to support an 800 kg biomass fish hatchery [11].

Additionally, an experimental trial tested the capabilities of a Rapid Sand Filter (RSF) and a hybrid system combining an RSF with a Slow Sand Filter (SSF) for controlling water turbidity, the microbial growth potential of *Pseudoalteromonas songiae* and the level of biofouling in culture tanks for juvenile dusky grouper over a 31 day observation period [25]. The fish culture tanks had a capacity of 1000 liters with a juvenile fish density of 4 individuals per tank and average initial biomass of 1.559 grams. The sand media in the RSF had a diameter of 0.6 mm with a uniformity coefficient of 1.7 and was operated at a hydraulic loading rate of 12 $m^3/m^2/h$. In comparison, the sand media in the SSF had a diameter of 0.1mm with a uniformity coefficient of 2.0 and was operated at a hydraulic loading rate of 0.1 $m^3/m^2/h$. The results from this research reported that the application of the hybrid filter combining RSF with SSF resulted in lower turbidity, achieving less than 1 NTU, reduced microbial growth and effective biofilm control in fish culture tanks compared to the application of the RSF alone [25].

Design of Biofilters in Recirculating Aquaculture Systems

Design and Performance Evaluation of Trickle Filters for Panulirus sp. Lobster Rearing

The design of biofilters for RAS is a crucial aspect of water quality management to support the growth of spiny lobster (*Panulirus sp.*). This design process involves a series of steps, including waste load analysis, selection of biofilter media and calculation of the necessary biofilter dimensions and capacity. The following are the stages of biofilter design implemented in *Panulirus sp*. lobster aquaculture research [26].

Waste Load Calculation

The primary waste that must be removed in aquaculture systems is ammonia (NH_3), produced through aquatic organisms' metabolic processes. The presence of ammonia in water must be controlled to maintain safe levels for lobsters. The total ammonia nitrogen (TAN) load can be calculated based on the feed's feeding rate and protein content. Using the following formula, the daily TAN load is determined as follows:

$$P_{\text{TAN Load}}\left(\frac{\text{kg}}{\text{day}}\right) = F_{\text{Feeding rate}}\left(\frac{\text{kg}}{\text{day}}\right) \times \; PC_{\text{Feed's protein concentration}} \times 0.144 \quad (1)$$

Where:

- Feeding Rate refers to the feeding rate, calculated as the percentage of feed relative to the lobster's body weight,
- Protein Concentration represents the protein content in the feed.

For example, in this design, a feeding rate of 10% of the total lobster weight, with a feed protein concentration of approximately 35%, results in a TAN load that must be managed.

Biofilter Capacity Calculation

The biofilter design begins with measuring dimensions based on the system's capacity to process the Total Ammonia Nitrogen (TAN) load. The design criteria for the biofilter in this study are based on several key assumptions that influence the capacity and dimensions of the designed biofilter system. The first assumption is that the harvest weight of lobsters is estimated at 40 kg, with the water temperature maintained at 28°C to optimize lobster metabolism. The organic load is calculated based on a daily feeding rate of 10% of the total lobster weight, ensuring sufficient feed to support growth and health.

The lobster stocking density is set at 5.7 kg/m³, representing the cultivation density per unit volume of water. Additionally, the system is designed with a water turnover rate of half a complete cycle per hour, supporting optimal water quality in the recirculating aquaculture system. The filter media is a sponge with a void fraction of 0.92, allowing efficient water flow distribution and supporting nitrification. Furthermore, the sponge is selected as the filter media due to its specific surface area (SSA) of 1600 m²/m³, providing a sufficient surface area for nitrifying bacteria to grow and convert ammonia into nitrate, thereby maintaining safe water quality for lobsters. The biofilter dimensions are calculated using the following formulas:

$$W_{feed\ weight}\ (kg) = total\ harvest\ weight\ (kg)\ \times\ Feeding\ rate\ (\%) \quad (2)$$

$$Oxygen\ demand\ (kg) = 0.25\ \times\ W_{feed\ weight}(kg) \quad (3)$$

$$V_{total\ water\ volume}\ (m^3) = \frac{total\ harvest\ weight\ (kg)}{lobster\ density(\frac{kg}{m^3})} \quad (4)$$

$$A_{biofilter}(m^2) = \frac{P_{TAN\ load}\ (\frac{g}{day})}{r_{TAN}\ (\frac{\frac{g}{m^2}}{day})} \quad (5)$$

$$V_{biofilter}(m^3) = \frac{A_{biofilter}\ (m^2)}{a(\frac{m^2}{m^3}\ biofilter\ media)} \quad (6)$$

$$S_{cross\ sectional\ area}(m^2) = \frac{Q_{biofilter}\ (\frac{m^3}{day})}{HLR_{Hydraulic\ loading\ rate}(\frac{\frac{m^3}{m^2}}{day})} \quad (7)$$

$$H_{biofilter\ height}\ (m) = \frac{V_{biofilter}\ (m^3)}{S_{Cross\ sectional\ area}\ (m^2)} \quad (8)$$

This study adjusted the biofilter design to a hydraulic flow rate of 200 m^3/m^2/day, with a required water volume of approximately 7 m^3 for the system. Based on calculations, the necessary biofilter volume is approximately 0.1 m^3, with a cross-sectional area of 0.2 m^2 and a biofilter height of 0.24 m.

Biofilter Performance Calculation.

The performance of the biofilter is assessed by monitoring the reduction in TAN concentration in the water during the recirculation process. This measurement is conducted by tracking TAN concentrations at the biofilter inlet and outlet every 24 hours using the grab sampling method. The TAN removal rate is calculated using the following formula:

$$VTR = \frac{([TAN]input - [TAN]output)\ .\ Q_{filter\ flow\ rate}\ (m^3 d^{-1})}{V\ media\ (m^3)} \quad (9)$$

Where:

- [TAN] represents the TAN concentration at the biofilter inlet and outlet,
- Q is the water flow rate through the biofilter,
- V is the volume of the biofilter media.

$$r^{TAN}=a[TAN]^n \pm b \quad (10)$$

[TAN] represents the TAN concentration in the influent solution, rTAN refers to the Volumetric TAN Removal Rate (VTR), a is the reaction rate coefficient for TAN removal, b is the intercept and n indicates the reaction order for TAN removal. In this study, the average TAN removal rate was 23.33 g TAN/m^3/day, demonstrating that the biofilter is highly efficient in reducing ammonia levels in the water.

Application and Performance Evaluation.

The results from the biofilter design calculations and performance testing indicate that the biofilter system effectively maintains optimal water quality for *Panulirus sp*. lobster rearing, with an average TAN reduction of 23.33 g TAN/m^3/day. This biofilter performance surpasses that of previous studies using different filter media. Furthermore, the system successfully supported lobster survival rates of up to 97.8%, demonstrating that the biofilter design effectively maintains the water quality for *Panulirus sp*. rearing.

Design of Submerged Biofilter for *Litopenaeus vannamei* Shrimp Rearing.

A study has been conducted on a series of designs and implementations of submerged filters for vaname shrimp rearing in RAS [14]. Several steps in this study are outlined below.

Determination of Design Criteria.

A submerged fixed-bed filter was designed with a total water volume of 8 m^3, intended for shrimp farming at a stocking density of 400 shrimp/m^3, with an expected total harvest of 46 kg of shrimp. The filter capacity was designed to be 1.5 times larger than the total harvest weight to prevent water overflow. The water quality criteria for shrimp farming included maintaining dissolved oxygen levels between 6-7 mg/L and keeping Total Ammonium Nitrogen (TAN) concentrations below 1.8 mg/L. Several assumptions were made in the design process, including a feeding rate of 3% of the shrimp's body weight, a feed protein content of 30%, a filter efficiency of 50% in removing TAN, a nitrification rate of 0.45 g TAN/m^2/day and a filter media surface area of 1200 m^2/m^3. The daily TAN load for the submerged fixed-bed filter was calculated using the following equation:

$$P_{TAN\ Load}\left(\frac{kg}{day}\right) = F_{Feeding\ rate}\left(\frac{kg}{day}\right) \text{ x } PC_{Feed's\ protein\ concentration} \text{ x } 0.065 \quad (11)$$

The biofilter dimensions were calculated using equations 2-7. Based on the calculations performed, the depth of the filter media used is 0.3 meters, with a filter media surface area of 1200 m^2/m^3, providing sufficient area for the growth of nitrifying microorganisms. The volume of the filter media used is 0.07 m^3, with the required nitrification surface area of 83.23 m^2. Additionally, the diameter of the filter's base area is 0.543 meters, ensuring optimal water flow distribution. Based on these calculations, the required filter media volume remains at 0.07 m^3, supporting optimal the biofiltration process.

Experimental Testing

Experimental testing was conducted to assess the designed biofilter's performance based on the calculation result. Shrimp weighing 0.74 ± 0.02 grams were stocked in each tank at a density of 400 shrimps/m^3 for 60 days. Feed was provided five times a day using CJ shrimp feed, which contains approximately 32-35% protein, with an amount of feed equalling 3% of the total shrimp weight. The RAS system was operated continuously for 24 hours without seawater exchange, but freshwater was periodically added to ensure that the salinity remained within the range of 23-25 ppt.

Results Achieved

The biofilter system applied in the Recirculating Aquaculture System (RAS) demonstrated high effectiveness in processing Total Ammonia Nitrogen (TAN), successfully reducing TAN concentrations to levels considered safe for shrimp farming, i.e., below 1.8 mg/L [14]. Although there was an increase in TAN concentrations on day 50 due to the accumulation of organic material from leftover feed, the filtration system could still control TAN levels within acceptable ranges. Additionally, water quality parameters such as nitrite (NO_2^-), nitrate (NO_3^-), temperature, pH and dissolved oxygen remained within optimal conditions for the growth and health of *Litopenaeus vannamei* shrimp. The performance of this system also provided significant environmental sustainability benefits, as it did not require regular seawater exchange and implemented a zero wastewater disposal system, thereby reducing environmental pollution in the surrounding aquatic ecosystem.

Conclusion

The selection of the type and design of the biofilter in RAS is a crucial factor in determining the system's effectiveness in maintaining water quality and supporting the health of cultured organisms. Each type of biofilter, such as fixed media filters, moving bed bioreactors (MBBR), trickling filters and fluidized bed filters, has its characteristics, advantages and challenges in the nitrification process and nitrogen waste treatment. The choice of biofilter type and design should be tailored to the specific needs of the RAS system, considering technical aspects, costs and ease of maintenance. The correct selection and design of the biofilter are expected to result in an optimal RAS system.

References

1. Liu W, Fan XY, Li X, Fan XY. Enhanced biofiltration coupled with ultrafiltration process in marine recirculating aquaculture system: Fast start-up of nitrification and long-term performance. Journal of Water Process Engineering 2024; 58: 104901. https://doi.org/10.1016/j.jwpe.2024.104901.
2. Prastowo B, Penataseputro T. Microbial Diversity of Biological Filters in Recirculating Aquaculture Systems for Sand Lobster (*Panulirus homarus*) Rearing. IOP Conference Series Earth and Environmental Science 2023;1273. https://doi.org/10.1088/1755-1315/1273/1/012064.
3. Neissi A, Rafiee G, Rahimi S, Farahmand H, Pandit S, Mijakovic I. Enriched Microbial Communities for Ammonium and Nitrite Removal from Recirculating Aquaculture Systems. Chenosphere 2022; 295: 133811. https://doi.org/10.1016/j.chemosphere.2022.133811.
4. Jafari L, Montjouridès MA, Hosfeld CD, Attramadal K, Fivelstad S, Dahle H. Biofilter and degasser performance at different alkalinity levels in a brackish water pilot scale recirculating aquaculture system (RAS) for post-smolt Atlantic salmon. Aquacultural Engineering 2024; 106: 102407. https://doi.org/10.1016/j.aquaeng.2024.102407.
5. Almeida JCR, Bega JMM, Leite LDS, Oliveira JND, Albertin LL, Matsumoto T. Membrane Aerated Biofilm Reactor in Recirculating Aquaculture System for Effluent Treatment. Environmental Technology 2023; 44(26): 4071- 4083. https://doi.org/10.1080/09593330.2022.2078674.
6. Shitu A, Liu G, Muhammad AI, Zhang Y, Tadda MA, Qi W *et al*. Recent advances in application of moving bed bioreactors for wastewater treatment from recirculating aquaculture systems: A review. Aquaculture and Fisheries 2022; 7(3): 244–258. https://doi.org/10.1016/j.aaf.2021.04.006.
7. Wang L, Zhu N, Shaghaleh H, Mao X, Shao X, Wang Q *et al*. The Effect

of Functional Ceramsite in a Moving Bed Biofilm Reactor and Its Ammonium Nitrogen Adsorption Mechanism. Water 2023; 15(7): 1362. https://doi.org/10.3390/w15071362.

8. Rocher V, Mailler R, Mèche P, Pichon S, Bernier J, Guerin S *et al*. (2019). Clogging limitation of nitrifying biofilters: BiostyrDuo® process study. Water Practice & Technology. 2019; 14(1): 43–54. https://doi.org/10.2166/WPT.2018.107.

9. Fernandes PM, Steigum E, Höglund E, Rojas-Tirado PA, Åtland Å. Hydrogen sulphide dynamics in recirculating aquaculture systems with moving or fixed bed biofilters: A case study in two commercial salmon smolt producing farms in Norway. Aquacultural Engineering 2024; 104: 102392. https://doi.org/10.1016/j.aquaeng.2024.102392.

10. Xiao R, Wei Y, An D, Li D, Ta X, Wu Y *et al*. A review on the research status and development trend of equipment in water treatment processes of recirculating aquaculture systems. Reviews in Aquaculture 2018; 11(3): 863–895. https://doi.org/10.1111/raq.12270.

11. Pfeiffer TJ, Ott BD. Biofiltration reactivation kinetics of a Cyclobio fluidized sand filter in a warmwater recirculating aquaculture system. North American Journal of Aquaculture 2023; 85(2): 166-173. https://doi.org/10.1002/naaq.10282.

12. Proano-Pena G, Carrano AL, Blersch DM. Analysis of very-high surface area 3D-printed media in a moving bed biofilm reactor for wastewater treatment. PLoS ONE 2020; 15(8): e0238386. https://doi.org/10.1371/journal.pone.0238386.

13. Duan H, Zheng M, Li J, Liu T, Wang Z, Shrestha S *et al*. High hydraulic loading rates favored Mainstream partial nitritation: Experimental Demonstration and Model-Based analysis. ACS ES&T Water 2023; *3*(2): 556–564. https://doi.org/10.1021/acsestwater.2c00569.

14. Thesiana L, Adiyana K. Design of submerged fixed bed filter for high density shrimp culture in recirculating aquaculture system. IOP Conference Series Earth and Environmental Science 2021; 695(1): 012025. https://doi.org/10.1088/1755-1315/695/1/012025.

15. Laza EA, Caba IL, Olan M, Vladut V. Biological water treatment in a recirculating aquaculture system. E3S Web Conference 2021; 286: 03013. https://doi.org/10.1051/E3SCONF/202128603013.

16. Pulkkinen JT, Eriksson-Kallio AM, Aalto SL, Tiirola M, Koskela J, Kiuru T *et al*. The effects of different combinations of fixed and moving bed bioreactors on rainbow trout (*Oncorhynchus mykiss*) growth and health, water quality and nitrification in recirculating aquaculture systems. Aquacultural Engineering 2019; 85: 98–105. https://doi.org/10.1016/j.aquaeng.2019.03.004.

17. Supriyono E, Rasul N, Budiardi T, Hastuti YP, Adiyana K, Thesiana L. A study on the effect of different colours of culture tanks in nursery, on the production performance, biochemical composition of flesh and physiological responses of whiteleg shrimp (*Litopenaeus vannamei*). Aquaculture Research 2021: 52(9): 4086–4093. https://doi.org/10.1111/are.15246.

18. Lu J, Zhang Y, Wu J, Wang J. Nitrogen removal in recirculating aquaculture water with high dissolved oxygen conditions using the simultaneous partial nitrification, anammox and denitrification system. Bioresource Technology 2020; 305: 123037. https://doi.org/10.1016/j.biortech.2020.123037.

19. Zhang H, Cao X, Wu X, Yu Y, Zhang Y, Yang L *et al*. Pilot-scale investigation of an advanced biofloc technology for treating Pacific white shrimp effluent: Performance and insight mechanisms. Aquaculture 2025; 741552. https://doi.org/10.1016/j.aquaculture.2024.741552.

20. Watari T, Hatamoto M, Yamaguchi T, Okubo T, Tyagi VK. Sponge-based trickling filter for nitrogen removal: mechanism, application and prospects. In Yaser AZ, Lamaming J, Johnson D, Hilal N, editors. Nutrients and Colored Compounds in Wastewater Advanced Treatment and Recovery. Elsevier eBooks; 2025, pp.5-17. https://doi.org/10.1016/b978-0-443-21701-2.00003-9.

21. Watari T, Vazquez CL, Hatamoto M, Yamaguchi T, Van Lier JB. Development of a single-stage mainstream anammox process using a sponge-bed trickling filter. Environmental Technology 2020; 42(19): 3036–3047. https://doi.org/10.1080/09593330.2020.1720309.

22. Akamine T, Nagai M, Watari T, Netsu H, Adlin N, Satanwat P *et al*. Nitrification characteristics and microbial community changes during conversion of freshwater to seawater in down-flow hanging sponge reactor. Ecotoxicology and Environmental Safety 2024; 283: 116839. https://doi.org/10.1016/j.ecoenv.2024.116839.

23. Kotcharoen W, Watari T, Adlin N, Nakamura Y, Satanwat P, Pungrasmi W *et al*. Effect of salinities on nitrogen removal performance of DHS-USB system and growth of *Epinephelus bruneus* in closed recirculating aquaculture system. International Biodeterioration & Biodegradation 2021; 164: 105299. https://doi.org/10.1016/j.ibiod.2021.105299.

24. Godoy-Olmos S, Jauralde I, Monge-Ortiz R, Milián-Sorribes MC, Jover-Cerdá M, Tomás-Vidal A *et al*. Influence of diet and feeding strategy on the performance of nitrifying trickling filter, oxygen consumption and ammonia excretion of gilthead sea bream (*Sparus aurata*) raised in recirculating aquaculture systems. Aquaculture International 2022; 30(2): 581–606. https://doi.org/10.1007/s10499-021-00821-3.

25. De Oliveira FF, Moreira RG, Schneider RP. Evidence of improved water quality and biofilm control by slow sand filters in aquaculture – A case study. Aquacultural Engineering 2019; 85: 80–89. https://doi.org/10.1016/j.aquaeng.2019.03.003.

26. Thesiana L, Adiyana K, Zulkarnain R, Moersidik SS, Gusniani I, Supriyono E. Ecofriendly land-based spiny lobster (*Panulirus sp*.) rearing with biofilter application in recirculating aquaculture system. IOP Conference Series Earth and Environmental Science 2020; 404(1): 012082. https://doi.org/10.1088/1755-1315/404/1/012082.

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2

CHAPTER

Technological Innovations in Recirculating Aquaculture System (RAS)

Riza Zulkarnain
Research Center for Fishery, National Research and Innovation Agency (BRIN)

Dendy Mahabror
Research Center for Fishery, National Research and Innovation Agency (BRIN)

Suhardi Atmoko Budi Susilo*
Research Center for Fishery, National Research and Innovation Agency (BRIN)

Puput Dani Prasetyo Adi
Research Center for Telecommunication, National Research and Innovation Agency (BRIN)

I Dewa Putu Hermida
Research Center for Electronics, National Research and Innovation Agency (BRIN)

Desak Gede Sri Andayani
Research Center for Environmental and Clean Technology, National Research and Innovation Agency (BRIN)

Pamungkas Daud
Research Center for Telecommunication, National Research and Innovation Agency (BRIN)

Goib Wiranto
Research Center for Electronics, National Research and Innovation Agency (BRIN)

Asmanik
Research Center for Mariculture, National Research and Innovation Agency (BRIN)

Corresponding Author: suha045@brin.go.id

Abstract

The RAS system is certain to be the best solution in terms of fish farming, it can even be 90% effective in maintaining water quality and also its durability in the cultivation process. RAS can handle the problem of aquaculture wastewater discharged into the environment and can be applied to various types of fish that have high marketability, the Internet of Things (IoT) system applied to RAS can optimally provide real-time information that can be combined with actuator system that can automatically provide warnings, perform automatic water changes and continue to monitor water quality in real-time, this can provide essential benefits for the fish farming system. IoT-based systems for RAS can be combined with various types of sensors that can perform monitoring systems such as water pH sensors, water turbidity sensors, water temperature sensors, Dissolved Oxygen (DO) sensors, Salinity Sensors, Nitrite and Nitrate Sensor that provide detailed information about the condition of the water environment in the cultivation system and also an automatic fish feeding system. While IoT, especially using LoRaWAN can even be combined with Artificial Intelligence (AI) systems to get more precise results about the condition of fish and the cultivation system as a whole.

Keywords: IoT, smart sensors, AI, RAS, LoRaWAN

Introduction

Internet of Things (IoT) technology plays a major role in building intelligent monitoring systems for aquaculture, including Recirculating Aquaculture Systems (RAS). RAS is an aquaculture system that uses filtering and water treatment technology that can be continuously used in the process of maintaining fish farming. This system can minimize aquaculture waste that will be discharged into the environment. There are several components of RAS, including tanks for fish rearing, mechanical filtration systems used to remove suspended solids, Biofilters used to convert ammonia to nitrate through nitrifying bacteria, aeration/oxygenation systems used for dissolved oxygen, temperature regulation systems and also sterilization components such as UV.

The advantages of RAS are water savings of up to 90%, compared to conventional systems, can be operated in locations with limited water sources, optimal control [1] of water quality parameters, year-round production, minimization of disease risk and better waste management. RAS [2] can be applied to various types of fish farming that have high selling value such as salmon, grouper, snapper and also catfish, this technology continues to be a future aquaculture solution. Meanwhile, the Internet of Things (IoT) in the RAS system will greatly assist in the monitoring and automation process such as systems that require actuators for solenoid valves, for example, which are used for automatic wastewater disposal if it looks cloudy, have an abnormal water pH and also other factors that inhibit the growth of aquaculture.

Moreover, In more detail, the IoT system in RAS is shown in the following points, including increasing the efficiency, productivity and sustainability of aquaculture systems that can provide detailed information about the monitoring system that is being carried out, including real-time water quality monitoring, water quality has a complete range of content such as temperature, dissolved oxygen, pH, ammonia, nitrite, nitrate and CO_2 factors, these data can be collected into one real-time in the conditions being monitored and also special is the monitoring system carried out at a distance. In this case, if monitoring is carried out, there must be several factors that cause data discrepancies, including sensor data, especially water pH for example. So IoT can provide a warning system that requires users to open and close valves using automation, for example Solenoid Valve to drain waterways.

Specifically about system automation in IoT RAS [3], including automatic pump settings, aerators and filtration systems based on sensor data, automation of feeding according to schedules, temperature settings and lighting systems are also parameters that need to be added and become more complex analysis if in-depth research needs to be done on the light used. After the above factors are comprehensively created and analyzed, specific data analysis and predictive systems are needed by collecting data or creating datasets if the specific analysis is needed for research, collecting big data for pattern and trend analysis, artificial intelligence algorithms for predicting potential problems before they occur and optimizing the use of energy [4], as well as resources.

IoT-LoRaWAN can be developed to improve the quality of application servers, management of data transmission from end-devices, gateway settings, distance management, transmit data management and other essential elements. Remote transmission management settings are needed to support the quality of the data being transmitted. The settings include the development of control systems through smartphone applications and WEB platforms, remote system intervention during emergency conditions and real-time notifications for critical conditions via SMS, email or application notifications. The next benefit of IoT technology for RAS is supply chain integration, including automated inventory tracking (feed, chemicals, etc.), monitoring of fish growth and biomass and prediction of harvest time and production yield. It can also perform real-time monitoring of energy efficiency such as optimization of electricity usage for pumps and aerators, automatic settings to reduce energy consumption at certain times and integration with renewable energy systems.

Application IoT in RAS

Several applications in RAS [5] have been conducted by several researchers through research, including Efficient water use is essential for maintaining sustainable practices and this can be achieved through methods such as employing recirculating aquaculture systems (RAS), which recycle water within aquaculture facilities and utilizing rainwater harvesting to reduce reliance on external water sources [6-8]. An Aquaponic-RAS technology was able to maintain water quality parameters within acceptable ranges for catfish aquaculture, resulting in good production indicators, including a high survival rate (85.5%), good feed conversion ratio (1.1) and high harvest yield (26 kg/m^3), furthermore can maintain water quality for reuse and increase catfish yields by about 13% compared to conventional methods which also stand for tilapia [9].

IoT in RAS has an important role in terms of modernization in the aquaculture system, with a digital technology integration system, IoT, especially LoRaWAN, which can provide novelty in terms of monitoring, control and optimization of the cultivation process. Specifically shown in the real-time water parameter monitoring system by looking at several influencing factors such as temperature, water pH, dissolved oxygen, ammonia and nitrate. These sensor data are sent continuously to servers such as the LoRaWAN Application Server. The IoT RAS system is also capable of providing automated systems, such as automatic feeding using a certain algorithm, automatic setting of water circulation and filtration systems and adjustment of oxygen levels and temperature based on realtime conditions. As well as performing data analysis and prediction by conducting historical data to analyze patterns and trends, creating an artificial intelligence algorithm that can predict problems that will occur and optimize the use of resources based on the data obtained.

IoT RAS is also able to be optimized in terms of notification and warning systems [10], sensor data such as sensor data mismatches will be able to be added with a notification system that can provide early warning of critical or abnormal conditions in the environment, especially aquaculture. The notification system can be given, for example, directly on the manager's mobile device so that it can provide a quick response to reduce mortality in fish farming. In addition to the warning system energy management, energy can also be monitored and used as an essential indicator for the warning system. Energy can also be optimized by providing a deep sleep system so that at certain times the system can rest when not sending data. Energy management can also be optimized by using energy for pumps, aerators and heating or cooling systems to reduce operational costs [11].

IoT systems can be built with several Nircable devices or devices such as WiFi, Bluetooth, LoRaWAN, GSM and other devices, the point is to be able to send data to the internet server with a long distance capable of providing sensor reports in real-time. Similarly, IoT on RAS, the system can provide data remotely through Mobile or WEB applications which are essentially able to provide data in real-time without having to be at the location of data collection. So that a quick response can be made. The essence of building an IoT-RAS system on the application server, WEB App or Mobile App, is a control system that can carry out commands from the warning system to turn on the water valve, in this case, the solenoid valve, for example, to perform an automatic system, not only monitoring, but also performing a system that can solve problems such as automatic replacement of cultivation water based on a warning system obtained from sensor data that does not match expectations. The integration of IoT and AI can result in the optimization of more sophisticated automation systems, IoT and AI can predict aquaculture systems such as estimating the number of harvests based on growth data, integrating production data with supply chain management systems and ensuring traceability of aquaculture products.

Smart Sensors in RAS

Smart Sensor Technology

In the first experiment, building a monitoring system for fish and shrimp farming using LoRaWAN, we used various sensors in a multi-point manner sent to the server, so smart technology for RAS is needed through multiple sensors this is the right step because the more sensors applied to the system to be built will be able to provide precise results and also be able to provide system automation that will be very helpful for pond farmers and fish farmers. Some of the sensors that I have mentioned before are among others Water Quality Monitoring Sensors and dissolved Oxygen (DO) Sensors, specifically DO Sensors, Continuous monitoring of oxygen levels using optical or electrochemical sensors with wireless connectivity can be maximized to get more precise results from real-time water conditions, DO is one of the most important factors in the fish farming process for good oxygen coverage and for fish survival. Next is the water pH sensor which can provide information about pH specifically and in real time, then is the water temperature sensor.

Good sensors such as waterproof digital thermometers can provide high precision values (±0.1°C). Then Ammonia/Nitrite/Nitrate Sensors are ion-selective electrodes or optical sensors to detect nitrogen compounds. Conductivity/Salinity Sensor is a digital measurement of water conductivity and salinity with automatic calibration.

In addition to these sensors, there are Flow and Level Sensors, Ultrasonic Flow Meters that are non-invasive measurements of water flow in pipes and Pressure-based Level Sensors that monitor water levels in tanks and reservoirs and Optical Level Sensors to detect water levels without direct contact. In addition to the above sensors, there are Biometric Sensors which are described as a Computer Vision System which is an AI-powered camera for fish counting, size estimation and behavioral analysis, Acoustic Sensors which are sensors capable of detecting fish activity and feeding behavior through sound analysis and Biomass Estimation Sensors which are systems that use various technologies (optical, acoustic or weight-based) to estimate the total biomass of fish. There are also Environmental Sensors including CO_2 Sensors capable of measuring carbon dioxide levels in water and air, Light Sensors capable of monitoring light intensity and spectral composition and Turbidity Sensors capable of measuring water clarity and suspended solids.

Several data transmission methods continue to be developed into a system that has superior performance, such as data transmission, hardware, methods such as Adaptive Data Rate (ADR), Listen Before Talk (LBT), Long-Range Frequency Hopping Spread Spectrum (LR-FHSS), ALOHA and others. We can develop or integrate systems with different hardware such as LoRa, ZigBee and WiFi combined or integrated as an integrated IoT system, we can call it Cross Technology Communication (CTC) by doing various combinations, especially in the Cloud or IoT Gateway, Edge Computing Devices and Wireless Sensor Network. This will be a more detailed and comprehensive development of the IoT system, especially telecommunications, in terms of analyzing its use. Ultimately, these smart sensor technologies transform RAS operations through real-time monitoring, predictive analysis and automated control systems, resulting in optimized production, reduced risk and improved sustainability in intensive aquaculture.

Benefit of IoT in RAS

The diversification of aquaculture, particularly in tilapia farming, is increasingly recognized as a crucial strategy for enhancing resilience against environmental uncertainties. This approach not only addresses the challenges posed by climate change but also improves the sustainability and profitability of aquaculture enterprises. It can be clarified that the application of IoT technology can provide high benefits to the RAS, including Operational Efficiency, especially in resource optimization with an estimated waste reduction of 15-30% from the automatic feed system. The next benefit is energy management with a 20-40% reduction in pump and aeration costs. With IoT, it is ensured that labor efficiency can be met by replacing labor with an IoT automation system that is only assisted by Internet servers and devices, as well as telecommunication, estimating this efficiency to 70% and a warning system that ensures the accuracy of the steps taken if there is an inaccuracy in the water environment, which is 30-50% ensuring that each device can work properly, with algorithms and scheduling that can provide realtime with accuracy in terms of timing [12].

The previous water quality was still using a conventional system, so with IoT RAS will be able to manage water well and water quality can also be improved. With IoT, monitoring can be done in real-time by conducting a detection system on water quality fluctuations in detail and in real-time, a quick response when there is a mismatch in sensor data such as water pH, oxygen and temperature. Historical data analysis talks about how to optimize water treatment and reduce the use of chemicals, namely the right dosage based on actual conditions, not scheduled maintenance.

The approach taken when monitoring LoRaWAN-based aquaculture in white leg shrimp is how to find out its health and the factors that cause AHPND disease that causes death. For this reason, the next year's research discusses how AHPND disease can be minimized or even eliminated with Artificial Intelligence (AI) and early disease detection through water sampling and also the process of taking shrimp samples, as well as fish. Early detection can be done by combining technology in Aquaculture systems such as RAS, only by comprehensively monitoring how water quality can be monitored and also detecting water and the cause of death of fish and shrimp that are being cultured. Furthermore, by using AI-Camera, fish growth can also be analyzed, by combining AI-Camera which produces datasets and then processing the datasets into a detailed and comprehensive form of analysis that shows growth from day to day, whether optimal or experiencing obstacles. The success of the IoT-RAS system can reach 25% and this is called significant success. In addition to growth, the movement of fish or shrimp can also provide conclusions about their health conditions, whether the shrimp or fish are experiencing stress, with a smart monitoring system, will be able to know in detail and provide conclusions about stress in fish or shrimp farming. By looking at all the parameters above, good water quality will certainly reduce the mortality rate of fish or shrimp farming, to increase the profit of pond farmers. With IoT-RAS, the estimated success in preventing mortality can reach >50% or around 30-60%.

The development is for decision-making using the database, including Performance Analysis i.e. comprehensive Dashboard for production metrics, Environmental Impact Assessment e.g. on Monitoring water usage and discharge quality, Predictive Analysis i.e. AI-based forecasting of production output and Integration with Business Systems: Connection between production data and financial/inventory systems. Furthermore, Economic Benefits include Reduced Operational Costs i.e. Reduction of overall operational costs by 15-30%. Improved ROI i.e. Increased production efficiency leading to faster return on investment, Premium Market i.e. Better quality control and traceability allowing access to premium markets and Insurance Benefits i.e. Some insurance companies offer reduced premiums for IoT-monitored systems.

Artificial Intelligence (AI) in RAS

AI Capabilities

Artificial Intelligence has a big role in building systems that are increasingly flexible, easy, such as IoT applications. IoT in RAS can be combined with AI systems, for example, when monitoring the agility or movement of cultured fish, it will be concluded in the future, namely the analysis process towards determining disease, for example. The integration of AI in RAS will be able to turn conventional systems into intelligent systems such as decision making and databases that can be managed optimally, for example in terms of using algorithms with the use of datasets.

Key applications of AI in RAS include real-time Water Quality Monitoring: AI algorithms process sensor data to continuously monitor parameters such as dissolved oxygen, pH, temperature and ammonia levels, predicting potential problems before they become critical. Next is Feed Optimization where machine learning models determine optimal feeding schedules and amounts based on fish behavior, growth rates and environmental conditions, thereby reducing wastage and improving feed conversion ratios [11, 13-16].

Next, previously discussed is Disease Detection, where computer vision systems can identify early signs of disease or abnormal behavior in fish by analyzing swimming patterns and physical appearance [17-19]. Futhermore is Energy Management, with AI able to optimize energy consumption across pumps, filters and other equipment based on system needs, thereby reducing operational costs. In addition, Predictive Maintenance draws from Algorithms by identifying potential equipment failures before they occur by analyzing performance patterns in filtration systems, pumps and other critical components. AI is also capable of Growth Prediction through machine learning models estimating harvest time and final biomass by analyzing historical data and current conditions. And AI is also useful in Water Treatment Optimization, through AI Systems adjusting the filtration and treatment processes in real-time to maintain ideal water conditions.

Integration in RAS

The diversification of aquaculture, particularly in tilapia farming, is increasingly recognized as a crucial strategy for enhancing resilience against environmental uncertainties. This approach not only addresses the challenges posed by climate change but also improves the sustainability and profitability of aquaculture enterprises.

System integration in Recirculating Aquaculture Systems (RAS) is an integrated approach that links various system components to create efficient and sustainable aquaculture operations [20]. Important aspects of system integration in RAS include Integrated Key Components, i.e. Monitoring and Control Systems, e.g. Sensors for water quality parameters (temperature, pH, dissolved oxygen, ammonia, nitrite), Automation systems for equipment settings and Centralized user interface for monitoring and control.

An integrated filtration system is a combined set of parameters including mechanical filtration used to remove solid particles. Biofilter for ammonia to nitrate conversion and water purification system (UV, Ozone), protein separation system and energy management. Energy management is more about power management for pump and aerator settings. Temperature regulation is integrated with heating and cooling systems and also the utilization of renewable energy using solar panels or biogas.

Moreover, the feeding system is built with several components including automatic feeders connected to the monitoring system. Feed optimization based on the condition of the biomass and the quality of the water and reduction of feed waste seen with water turbidity sensors or other specific sensors. A data management system consisting of centralized data of various parameters includes an early warning system for critical parameters and analysis and optimization of production.

Next, the benefits of system integration are operational efficiency, which is useful for reducing the presence of human resources or labor and replacing them with automation systems such as water replacement, energy monitoring and also feeding. And how to create a rapid response to changes in parameters, so as to be able to provide a rapid response to improve conditions to normal again. With the automation of sensors and the IoT RAS system, it will make water recycling effective, minimize waste and environmental impacts and optimize energy.And Sustainability, namely Reduction of water use through effective recycling, Minimization of waste and environmental impacts and Optimization of energy use.

The challenges that occur in integrated systems include technical complexity, which requires specialized expertise in aquaculture, electronics and programming, so this work can be completed with teamwork. Next is the cost of implementation, the high initial investment is on the device and installation side and next is the cost of maintaining an integrated system that is more extensive than a single system. Integrated systems are said to have more reliability due to the number of elements or backup hardware and software that can be a replacement for damaged or critical devices and contingency plans to avoid system failure.

Summary of Benefits

- **Enhanced Monitoring:** IoT and smart sensors provide continuous, real-time monitoring of water quality and fish health, ensuring optimal conditions in RAS [21].
- **Data-Driven Decisions:** AI processes the data collected by IoT devices and smart sensors, enabling predictive analytics and automated decision-making [22].
- **Sustainability:** These technologies help in maintaining water quality, reducing waste and improving the overall efficiency and sustainability of RAS [23].

Challenges and Considerations

- **Complexity:** Implementing IoT, smart sensors and AI in RAS requires significant technical expertise and investment [24-26].

- *Data Integration*: Ensuring seamless integration and communication between various devices and systems is crucial for the effective functioning of IoT and AI in RAS.

Conclusion

The integration of IoT, smart sensors and AI in recirculating aquaculture systems offers significant benefits in terms of monitoring, efficiency and sustainability. However, it also presents challenges that need to be addressed to fully realize its potential.

References

1. Xu J, Du Y, Zhang J, Chen F, Zhou L, Qiu T *et al*. A backwater technology for enhancing pollutants discharge from aquaculture tanks in a *Litopenaeus vannamei* recirculating aquaculture system: Performance and control models. Aquaculture Reports. 2025; 15(40):102642. https://doi.org/10.1016/j.aqrep.2025.102642
2. Cardenas-Cartagena J, Beferull-Lozano B, Elnourani M, Romero D. Risk-Aware Particle Filtering for State Estimation in Recirculating Aquaculture Systems. In 2022 56th Asilomar Conference on Signals, Systems and Computers, IEEE,Pacific Grove, 2022, 829-833. https://doi.org/10.1109/IEEECONF56349.2022.10051993
3. Singh M, Sahoo KS, Gandomi AH. An intelligent-IoT-based data analytics for freshwater recirculating aquaculture system. IEEE Internet of Things Journal. 2023;11(3):4206-4217. https://doi.org/10.1109/JIOT.2023.3298844
4. Dong Z, Wang Y. Optimization of power load and energy consumption in industrialized recirculating aquaculture system. IET Conference Proceedings CP842, 2023(12), IET, Hangzhou, 2023, 79-82. https://doi.org/10.1049/icp.2023.1875
5. Wu G, Liu HB, Ma C, Xu HM, Ren XZ, Sun W. Developments and application of fish school swimming model in recirculating aquaculture systems. Ocean Engineering. 2025;319:120196. https://doi.org/10.1016/j.oceaneng.2024.120196
6. Puspaningsih D, Supriyono E, Nirmala K, Rusmana I, Kusmana C, Widiyati A. Water quality, hematological parameters and biological performances of snakehead fish (*Channa striata*) reared in different stocking densities in a recirculating aquaculture system. Aquaculture,

Aquarium, Conservation & Legislation. 2019;12(5):1546-58.

7. Puspaningsih D, Setijaningsih L, Setiadi E, Taufik I. Effect of different stocking density of snakehead fish (*Channa striata*) cultured in recirculation aquaculture system. In E3S Web of Conferences 2021, 322, EDP Sciences, Denpasar, 2021, 02005. https://doi.org/10.1051/e3sconf/202132202005

8. Setiadi E, Taufik I, Setijaningsih L, Ardi I, Puspaningsih D. Feeding frequency on survival, growth, blood glucose of glass eel, Anguilla bicolor bicolor cultured in a recirculating aquaculture system. In IOP Conference Series: Earth and Environmental Science 2023, 1221(1), IOP Publishing, Banda Aceh, 2023, 012037. https://doi.org/10.1088/1755-1315/1221/1/012037

9. Ekawati AW, Ulfa SM, Dewi CS, Amin AA, Salamah LN, Yanuar AT *et al*. Analysis of aquaponic-recirculation aquaculture system (A-Ras) application in the catfish (*Clarias gariepinus*) aquaculture in Indonesia. Aquaculture Studies. 2021; 21(3):93-100. http://doi.org/10.4194/2618-6381-v21_3_01

10. Libao FJ, Villaverde OS, De Luna NA, Comedia VJ, Luna MO, Atienza AM *et al*. Automated control and IoT-based water quality monitoring system for a *Molobicu*s tilapia recirculating aquaculture system (RAS). In 2024 IEEE Conference on Technologies for Sustainability (SusTech) 2024 Apr 14, IEEE, Portland, 2024, 410-415. https://doi.org/10.1109/SusTech60925.2024.10553538

11. Jie C, Yingying S, Junhui W, Yusheng W, Huiping S, Kaiyan L. Intelligent control and management system for recirculating aquaculture. In 2019 IEEE 2nd International Conference on Electronics and Communication Engineering (ICECE) 2019 Dec 9, IEEE, Xi'an, 2019, 438-443. https://doi.org/10.1109/ICECE48499.2019.9058567

12. Weiqiang C, Jessalin N, En TL, Sin LC. Evaluating metabolic rate and specific dynamic action in recirculating aquaculture systems: Influence of stocking density and feeding level in barramundi (*Lates calcarifer*). Aquaculture. 2025; 604:742503. https://doi.org/10.1016/j.aquaculture.2025.742503

13. Chen Z, Chang Z, Qiao L, Wang J, Yang L, Liu Y *et al*. Nitrogen removal performance and microbial diversity of bioreactor packed with cellulosic carriers in recirculating aquaculture system. International

Biodeterioration & Biodegradation. 2021; 157:105157. https://doi.org/10.1016/j.ibiod.2020.105157.

14. Zhao S, Zhang S, Liu J, Wang H, Zhu J, Li D *et al*. Application of machine learning in intelligent fish aquaculture: A review. Aquaculture. 2021; 540:736724. https://doi.org/10.1016/j.aquaculture.2021.736724
15. Chen F, Sun M, Du Y, Xu J, Zhou L, Qiu T *et al*. Intelligent feeding technique based on predicting shrimp growth in recirculating aquaculture system. Aquaculture Research. 2022; 53(12):4401-4413. https://doi.org/10.1111/are.15938.
16. Gupta S, Makridis P, Henry I, Velle-George M, Ribicic D, Bhatnagar A *et al*. Recent Developments in Recirculating Aquaculture Systems: A Review. Aquaculture Research. 2024; 2024(1):6096671. https://doi.org/10.1155/are/6096671
17. Khabusi SP, Huang YP, Lee MF, Tsai MC. Enhanced U-Net and PSO-optimized ANFIS for classifying fish diseases in underwater images. International Journal of Fuzzy Systems. 2024; 26(8):2518-2535. https://doi.org/10.1007/s40815-024-01743-x
18. Pham TN, Nguyen VH, Kwon KR, Kim JH, Huh JH. Improved YOLOv5 based deep learning system for jellyfish detection. IEEE Access. 2024; 12:87838-87849. https://doi.org/10.1109/ACCESS.2024.3405452
19. Rather MA, Ahmad I, Shah A, Hajam YA, Amin A, Khursheed S *et al*. Exploring opportunities of Artificial Intelligence in aquaculture to meet increasing food demand. Food Chemistry: X. 2024; 22:101309. https://doi.org/10.1016/j.fochx.2024.101309
20. Tarnecki AM, Brennan NP, Guttman L, Main KL. Variability in prokaryotic and eukaryotic periphyton communities in marine recirculating integrated multi-trophic aquaculture systems. Aquaculture. 2025; 600:742210. https://doi.org/10.1016/j.aquaculture.2025.742210
21. Jais NA, Abdullah AF, Kassim MS, Abd Karim MM, Muhadi NA. Improved accuracy in IoT-Based water quality monitoring for aquaculture tanks using low-cost sensors: Asian seabass fish farming. Heliyon. 2024; 10(8):e29022. https://doi.org/10.1016/j.heliyon.2024.e29022
22. Huang YP, Khabusi SP. Artificial Intelligence of Things (AIoT) Advances in Aquaculture: A Review. Processes. 2025;13(1):73. https://doi.org/10.3390/pr13010073

23. Mustapha UF, Alhassan AW, Jiang DN, Li GL. Sustainable aquaculture development: a review on the roles of cloud computing, internet of things and artificial intelligence (CIA). Reviews in Aquaculture. 2021;13(4):2076-91. https://doi.org/10.1111/raq.12559
24. Li H, Cui Z, Cui H, Bai Y, Yin Z, Qu K. A review of influencing factors on a recirculating aquaculture system: Environmental conditions, feeding strategies and disinfection methods. Journal of The World Aquaculture Society. 2023; 54(3):566-602. https://doi.org/10.1111/jwas.12976
25. Soares MS, Singh R, Kumar S, Jha R, Nedoma J, Marthuanghuaninek R *et al*. The role of smart optical biosensors and devices on predictive analytics for the future of aquaculture systems. Optics & Laser Technology. 2024;177:111049. https://doi.org/10.1016/j.optlastec.2024.111049
26. Waller U. A Critical Assessment of the Process and Logic Behind Fish Production in Marine Recirculating Aquaculture Systems. Fishes. 2024; 9(11):431. https://doi.org/10.3390/fishes9110431

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3

CHAPTER

Feed strategy and Management in Recirculating Aquaculture System (RAS)

Wahyu Pamungkas, Rasidi, Dewi Puspaningsih, Adam Robisalmi and Fajar Anggraeni*

Research Center for Freshwater Aquaculture,
National Research and Innovation Agency (BRIN)

Corresponding Author: anggraeni.anggra24@gmail.com

Abstract

Recirculating Aquaculture Systems (RAS) represent a breakthrough in sustainable aquaculture by reducing water usage and minimizing environmental impact through advanced water treatment and reuse technologies. Over the past four decades, RAS has integrated aquaculture with wastewater treatment, contributing to sustainability by reducing water withdrawal by up to 99% and lowering waste and antibiotic discharge. However, despite their benefits, RAS systems are capital-intensive and can face operational challenges, including environmental changes and fluctuating feeding or disinfecting routines. Efficient feed management plays a critical role in the success and sustainability of RAS operations. It is essential for optimizing fish growth, reducing waste and preserving water quality. As global demand for protein increases, improving feed management strategies in RAS is key to meeting these demands while ensuring environmental responsibility. Contemporary technologies such as automated feeders and alternative protein sources contribute to circular economic models that enhance farm productivity and fish health. This chapter explores the vital relationship between feed management, fish productivity and water quality in RAS, offering insights into strategies that can optimize feed use, reduce waste and lower costs. Recommendations for the future focus on adopting data-driven methodologies and automated systems to enhance RAS efficiency and sustainability.

Keywords: Feed management, recirculating aquaculture systems (RAS), sustainable aquaculture, water quality management, aquaculture technology

Introduction

Recirculating Aquaculture Systems (RAS) are breakthroughs for closed-loop facilities that mitigate water volume stress through treatment and reuse, providing a more environmentally friendly approach to fish farming [1]. Fortified in the past four decades, RAS technology is the integration of aquaculture and wastewater treatment, employing sophisticated aquaculture industry waste management [2]. These systems help sustain water sources by reducing water withdrawal by as much as 99%, lowering waste and antibiotic discharge and improving sustainability [1]. RAS systems usually contain solid waste collection, biofiltration, aeration, gas removal, aeration and disinfection [3]. The operational stability of RAS systems, as a closed-loop system consisting of multiple components, can heavily rely on the functionality of each segment; thus, the aquaculture products may suffer the repercussions of several uncontrollable factors, such as changing environmental conditions, feeding habits or disinfecting routines (Figure 1) [4].

However, there are significant capital costs and risks involved in implementing RAS. In any case, RAS systems are beneficial due to their continuous output, low environmental impact and adaptability to different control levels [3, 5]. In Indonesia, RAS has been implemented at several levels from small aquaponics to bigger systems with some boasting advanced technologies such as microbubbles [3]. With the advancement of technology, there is greater acknowledgment of RAS for development in sustainable aquaculture precisely because it seems to be increasingly essential [5]. Optimal performance of RAS requires an appropriate system configuration, efficient water treatment, solid feed structure, ongoing supervision, controllable shifts and adaptable logistical frameworks to retain value over time. One of the most prominent measures to guarantee the success of RAS operations is through efficient feed management.

Besides water treatment and system design, feeding management is fundamental for the sustainability goals of RAS systems. The role of feeding management in Recirculating Aquaculture Systems (RAS) is very critical relative to the growth and sustainability of the aquaculture environment. With the increasing global demand for protein, there is a need to improve feed management. Effective feed strategies optimize fish growth while reducing waste and preserving water quality by minimizing nutrient effluence and eutrophication from streams. Such practices offer solutions to fundamental problems associated with pollution and ecosystem degradation. Additionally, the incorporation of contemporary technologies like automated feeders and substitute protein sources improves sustenance in RAS operations. These methods lessen the use of conventional feed, promoting circular economic ideas that improve both farm productivity and fish health. Thus, sustainable developmental goals are in line with sufficiently effective feed management techniques in RAS, allowing aquaculture to meet protein demand in an environmentally responsible and sustainable manner.

Managing feed strategies is essential to achieving high productivity levels in aquaculture, especially in recirculating aquaculture systems (RAS). Enhanced productivity and feeding precision are the costliest elements of operation [6]. To maintain profit with RAS profitability, one must consider environmental conditions, feed composition, feed volume and frequency [4]. Separate stages of aquaculture employ distinct strategies, including green water technology for larvae and 80-90 percent satiation feeding during the grow-out phase [7]. Restrained feeding is an effective management strategy. Research involving juvenile *Colossoma macropomum* showed that ratifying food intake to once-per-week maintenance devoid of body reserves and performance maintained comparable levels to continuous feeding [8]. The optimal strategy of feed management in RAS focuses on minimizing the ratio of feed to output (conversion ratio), maximizing increase in weight (growth) and optimizing water quality [4, 7]. To improve growth, feed dynamics and system sustainability, precise feeding strategies need to be tailored for specific species and their culture stages.

The critical role that feed plays in fish health, productivity and system efficacy is highlighted in this chapter's comprehensive analysis of feed management and strategy in recirculating aquaculture systems (RAS). It emphasizes how important it is to select and give the right type and amount of feed and how this affects fish growth and water quality. The chapter enumerates feed management issues, such as feed waste and water contamination and discusses potential fixes. It looks at the relationship between feed and water quality, highlighting the harm that excessive or inefficient feeding causes to the system and providing ways to lessen these effects. Examined is the economic impact of feed management, showing how efficient feeding techniques can lower production costs and boost profitability. In conclusion, the chapter offers recommendations for feed strategy optimization using automated systems, feed monitoring technologies and data-driven methodologies to help RAS operators boost productivity, reduce costs and promote sustainability in aquaculture operations.

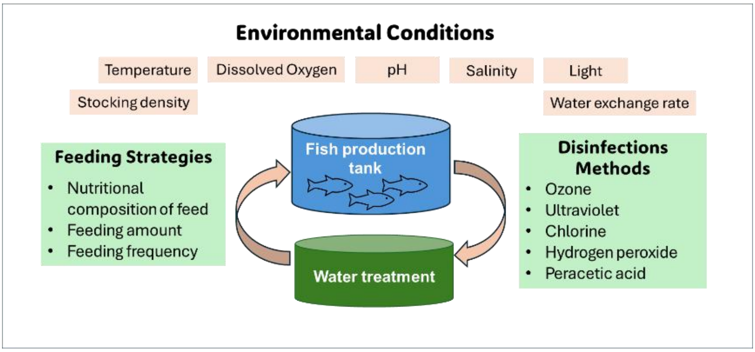

Fig 1: Key factors that affect the performance of recirculating aquaculture systems (RAS)

Principles of Feeding in Recirculating Aquaculture System

Nutritional Requirements of Aquatic Species in RAS

Efficient operation of recirculating aquaculture systems (RAS) depends on meticulous control of environmental conditions, feeding strategies and disinfection techniques [4]. Given its impact on fish development, health and waste production, nutrition is crucial in aquaculture [9]. Fish require about 40 essential nutrients, including proteins, carbohydrates, fatty acids, vitamins and minerals, with requirements varying by species and environment [10]. The development of affordable, nutritionally balanced diets is essential to sustainable aquaculture production [10, 9]. Maintaining appropriate ranges for temperature, salinity, dissolved oxygen, pH, stocking density and light is essential for optimal RAS performance [4]. Important considerations also include feeding strategies, such as feed composition, amount and frequency [4]. Understanding the nutritional needs of individual species is essential for creating effective diets and feeding procedures in aquaculture [9, 11].

It is crucial to comprehend the dietary needs of various species and to understand how good feeding techniques can also ensure optimal water quality and system performance. In addition to enhancing fish growth and survival, maintaining optimal nutrition in RAS is crucial for preserving water quality and system effectiveness. The accumulation of ammonia, nitrites and organic matter caused by overfeeding and fish waste can deteriorate water quality and increase the workload of biofiltration systems [12]. Precision feeding methods that match the nutrient supply with fish requirements are essential to lowering feed waste and nutrient loading in the system [4]. Advances in feed formulation, such as the use of probiotics, functional additives and novel ingredients, can improve fish health and nutrient utilization while reducing environmental impact [10, 11]. To enhance feed efficiency and optimize fish growth in RAS environments, automated feeding systems and real-time monitoring technologies can also be combined.

Feed Formulation and Selection

Feed formulation and selection are critical to the success of aquaculture in Recirculating Aquaculture Systems (RAS). Fish require diets that are prepared appropriately to satisfy their nutritional requirements while minimizing waste and the harm they cause to the environment. A well-balanced diet should contain the appropriate proportions of proteins, fats, carbohydrates, vitamins and minerals, all of which are tailored to the specific needs of cultured species [11]. Protein needs to be optimized for both sustainability and economic viability because it is often the costliest component of fish feed. Alternative protein sources such as plant-based proteins, insect meals and single-cell proteins are increasingly being researched to reduce reliance on fishmeal and improve the sustainability of aquafeeds [10].

Feed selection in RAS necessitates careful consideration of factors such as digestibility, pellet stability and water solubility in addition to nutritional composition, building on the need for optimal nutrition and water quality explained in the previous section. Beyond nutritional composition, RAS feed selection must consider characteristics like water solubility, digestibility and pellet stability. According to [12], high-quality feeds with high digestibility prevent excessive organic matter buildup and nutrient waste, which can also increase biofilter loading and deteriorate water quality. Fish feeding behaviors should be matched with pellet size, shape and floating or sinking characteristics for optimal consumption and minimal feed loss [13, 4]. The potential of functional feeds supplemented with immunostimulants, probiotics and prebiotics to increase feed efficiency, reduce disease outbreaks in RAS environments and enhance fish health is also drawing attention [9-11].

Advances in feed technology, such as precision extrusion and microencapsulation, enhance nutrient retention and bioavailability even more. Growth is maximized while nutrient waste and the feed conversion ratio (FCR) are reduced thanks to the accurate feed delivery enabled by automated feeding systems with real-time monitoring. Future studies on sustainable feed ingredients and innovative feeding methods will be necessary to improve the efficacy and resilience of RAS-based aquaculture.

Digestibility and Feed Conversion Ratio (FCR) Considerations

Feed Conversion Ratio (FCR) and digestibility are important indicators for evaluating feed efficiency and overall aquaculture system performance, especially in Recirculating Aquaculture Systems (RAS). Digestibility is a measure of how well fish can absorb and use nutrients from the feed, whereas FCR indicates the amount of feed required to produce one unit of fish biomass [9]. Improving these parameters is essential for RAS growth optimization, feed waste reduction and water quality preservation.

As mentioned previously, the quality of feed formulation has a direct effect on nutrient absorption. Adding to the importance of selecting high-quality, digestible feeds, highly digestible feeds enhance nutrient absorption and reduce faecal waste and uneaten feed, which can otherwise lead to the accumulation of organic matter and ammonia in RAS [12]. The digestibility of feed ingredients is influenced by several factors, including ingredient composition, processing methods and the presence of anti-nutritional factors [10]. Because of advancements in processing techniques and the addition of enzymes, plant proteins in aquafeeds are now more digestible; however, animal-based protein sources, such as fishmeal, are usually more digestible than plant-based substitutes [11]. Since lower FCR values indicate higher feed efficiency, FCR is an essential performance metric in aquaculture. FCR optimization is crucial to RAS's continued economic and sustainable viability. A balanced diet, cautious feeding methods and controlled environmental conditions can all help lower FCR [4]. While underfeeding may result in less-than-ideal growth and more competition among fish, overfeeding can cause poor feed utilization and deterioration of the water quality. In order to improve FCR and reduce feed losses, automated feeding technologies and real-time monitoring systems have been developed to control feed delivery based on fish appetite and metabolic needs [9].

Further research on species-specific digestibility and feed formulation methods will be necessary to improve nutrient utilization and reduce waste discharge in RAS. By enhancing digestibility and FCR, aquaculture operations can achieve higher productivity while maintaining environmental responsibility and system sustainability.

Feed Types and Their Application in RAS

Feed selection has a major impact on the success of Recirculating Aquaculture Systems (RAS) by influencing fish growth, feed efficiency and overall system sustainability. The choice of feed type has a direct impact on water quality control, waste production and nutrient use in RAS [9]. Commercial feeds, live feeds and alternative feeds are the three main types of feeds used in RAS and each has specific applications based on species requirements and production objectives. Selecting the right feed type for the species' nutritional needs and the system's operational goals is essential to maximizing system performance. Selecting the right feed ensures optimal digestion, minimizes waste accumulation and boosts system performance [4].

Commercial Feeds (Pellets, Extruded and Sinking Feeds)

Commercial feeds are the most widely used feed type in aquaculture because they provide fish and shrimp raised in RAS with a diet that is both balanced and nutritionally complete. These feeds, which range from pellets to extruded feeds to sinking feeds, are all designed to optimize feed intake and nutrient utilization for various fish species and stages of production [11].

- **Pellet:** Pelletized feeds are made by mechanical compression and come in sinking, slow-sinking and floating types. Because floating pellets allow farmers to monitor feed consumption and minimize waste, surface-feeding species favor them [14, 15].
- **Extruded feeds:** Feeds that have undergone high-temperature processing to improve water stability, nutrient availability and digestibility are known as extruded feeds. These feeds, which typically float, are ideal for fish, like catfish and tilapia [16].
- **Sinking feeds:** To ensure proper feed uptake, certain species, such as bottom-dwelling fish and shrimp, require sinking feeds. However, uneaten sinking feed can contribute to the buildup of organic waste in RAS if it is not adequately managed [12].

The species' feeding habits, its life stage and the general system design all influence the choice of the appropriate commercial feed type. This ensures efficient nutrient absorption and high-quality water [10].

Impacts of Feed Types on Water Quality

Feed selection has a direct impact on managing water quality in RAS because of the accumulation of ammonia, nitrite and organic matter caused by uneaten feed and metabolic waste [12]. Feed types have an impact on water quality in the following ways:

- Protein Content and Waste Production: Excessive protein intake can result in increased nitrogen excretion, which makes biofiltration and water exchange more important in RAS [9].
- Feed Digestibility and Solubility: Excessive fecal matter from poorly digested feeds can clog filters and reduce the system's oxygen supply [15].
- Pellet Stability: Diets that are extruded or microencapsulated have a higher water stability, which reduces the risk of feed leaching and nutrient loss into the system [16].
- Organic Load from Live Feeds: Live feeds can introduce organic waste and bacterial contaminants that alter the balance of the microbial community in biofilters [17].

According to [4], effective feed management strategies, including precise feeding schedules, suitable feed selection and automated feeding systems, are essential for minimizing the degradation of water quality and maximizing nutrient utilization in RAS.

Feeding Strategies in RAS

In recirculating aquaculture systems (RAS), feeding practices have a significant impact on fish growth, welfare and system performance. The optimal feeding frequency varies by species; for instance, Atlantic salmon grow best when fed four times a day [18], while juvenile pikeperch benefit from 8-hour intervals [19]. Feeding rate affects growth and nutrient utilization; 1.6% body weight per day is recommended for salmon [18] and 1% is recommended for stellate sturgeon [20]. While diet composition influences ammonia excretion and oxygen consumption, plant-based diets increase gilthead sea bream's oxygen demand [21]. Auto-demand feeding allowed for higher ammonia removal rates without compromising water quality [21]. Effective feeding techniques in RAS can optimize growth performance, feed utilization and system efficiency while maintaining fish welfare and environmental sustainability.

Feeding Frequency and Schedules

Feeding frequency and schedules play a major role in maximizing growth performance, health, feed efficiency and nutrient use in recirculating aquaculture systems (RAS). The frequency and timing of feed delivery have a direct impact on fish metabolic processes, feeding behaviour and nutrient utilization [22]. Higher feeding frequencies typically lead to better growth rates and nutrient retention levels, according to research on several species. Atlantic salmon showed improved growth and nutrient efficiency when fed at a rate of 1.6% body weight per day with four meals per day [18]. Similarly, the best-performing tambaqui young were those fed three times a day [23]. For young pikeperch, an 8-hour feeding interval was found to be optimal, balancing fish growth, survival and welfare [19]. However, optimal feeding strategies are also influenced by species, life stage and environmental factors. Proper feed management in RAS is essential for preserving water quality, ensuring efficient nutrient use and promoting sustainable aquaculture practices [4]. Further research is still needed to fine-tune feeding protocols for different species in RAS settings.

Automated Feeding Systems vs. Manual Feeding

Compared to manual feeding methods, recirculating aquaculture systems (RAS) with automated feeding systems offer several advantages. These systems can reduce human error, improve feeding accuracy and save labor for a range of aquatic animals [24]. When compared to handfeeding, automated adaptive feeders have been shown to increase fish yield by up to 52.3%, increasing profits. Recent automated feeding technology uses multi-task neural networks to dynamically adjust feeding intervals and rates based on fish behavior and uneaten feed pellets. This approach may help minimize feed waste and prevent under- or over-feeding because it has demonstrated high accuracy in tracking feeding activity (95.44%) and counting uneaten pellets [25]. These developments in automated feeding systems enhance fish welfare, sustainability and production efficiency in RAS and offer a promising solution for the growing aquaculture industry.

Automated feeding systems in recirculating aquaculture systems (RAS) are becoming increasingly important due to the aquaculture industry's rapid growth. These systems can reduce human error, increase feeding efficiency and reduce labor costs [24]. Automated feeders that can dispense various fish food types at predetermined rates and times are convenient for fish culturists [26]. Remote-controlled boats with built-in feed and medicine distribution containers are one of the innovative ideas [27]. To optimize RAS performance, it is crucial to monitor both direct parameters, like pH, temperature and dissolved oxygen, as well as indirect parameters, which are dependent on stock capacity. Fog computing technology can enhance data acquisition and processing in RAS by filtering and analyzing data at the edge, reducing network traffic and facilitating real-time decision-making [28]. These automation and data management advancements help meet the growing global demand for fish protein while promoting the aquaculture industry's sustainable growth.

Recirculating aquaculture systems (RAS) are an efficient and sustainable way to produce fish, but they require careful management of environmental conditions and feeding habits. RAS has investigated auto-demand feeding, automatic restricted feeding and manual feeding to satiation for gilthead sea bream; auto-demand feeding has the highest rates of ammonia removal [21]. A multi-task neural network technique has been developed to optimize feeding rates and intervals to reduce feed waste and prevent under- or overfeeding [25]. Several factors influence RAS performance, including temperature, salinity, dissolved oxygen, pH, stocking density, light, feed composition and feeding frequency [4]. Complete pelleted diets are necessary to meet nutritional needs because tilapia in RAS have fewer natural food sources than in their natural habitats. The dependable and efficient operation of RAS is supported by these advancements in environmental management and feeding practices.

Smart Feeder Technologies and Precision Feeding

Smart feeding systems for aquaculture have been the focus of recent research to optimize fish growth, welfare and environmental impact. These systems use a variety of technologies to track fish behavior and adjust feeding as necessary [29]. Developed a method to measure tilapia feeding intensity using optical flow based on shoal behavior in recirculating aquaculture systems (RAS). An Internet of Things (IoT) smart feeder with mobile app integration was developed by [30] for small-scale fish farmers. An AIoT precise feeding management system that adjusts feeding times based on water surface changes was presented by [31]. Study by [32] developed a clever behavior-based feeding system that reacts to fish activity with the goal of decreasing food waste and increasing the food conversion ratio. Lower environmental impact, improved fish welfare and more productive aquaculture settings are some potential benefits of these smart feeding technologies [29, 32].

Physiological and Behavioral Aspects of Feeding

Recent research has focused on the behavioral and physiological aspects of fish feeding in recirculating aquaculture systems (RAS). Studies have shown that water turbidity significantly affects feeding behavior; pikeperch that experience low turbidity eat less feed and experience increased stress [33]. Shoal behaviour analysis using statistical and optical flow techniques has been proposed to assess feeding intensity and optimise feeding schemes for tilapia [29]. Acoustic monitoring of Atlantic salmon kept in RAS tanks during feeding showed distinct soundscapes, including identifiable sounds from fish behavior and pellet delivery. According to [34], this implies that fish behavior and system performance can be tracked. Nevertheless, stress-induced chemicals released by fish in RAS water had no effect on the feeding motivation of other fish in the same system [35]. These findings highlight the importance of controlling RAS feeding by considering environmental and species-specific biology.

Feed Management and Its Impact on Water Quality

Relationship between Feed and Water Quality in RAS

Feed and water quality interact to maintain optimal conditions for aquatic species in recirculating aquaculture systems (RAS). Overfed shrimp cultures may have increased levels of total ammonia nitrogen (TAN), oxygen depletion and mortality [36]. The types of protein that fish consume can affect water quality parameters; RAS ion concentrations are affected by plant-based proteins. The number of potentially hazardous bacteria in RAS, such as Aeromonas hydrophila and Pseudomonas fluorescens, is positively correlated with fish biomass and feed quantity [37]. RAS-designed diets can improve water quality, decrease particle generation and prevent fish from accumulating as much nitrogen, phosphorus and zinc as traditional flow-through diets, all while maintaining fish growth and condition that is acceptable [38]. These findings highlight how important it is to modify feed composition and management to RAS conditions to optimize system performance and safeguard animal health.

Strategies to Minimize Waste and Improve Nutrient Utilization

Recirculating aquaculture systems (RAS) face challenges with waste management and nutrient utilization. Fish excretion and leftover feed account for most of the solid and dissolved waste in RAS [39]. Reducing waste and improving nutrient utilization can be achieved through improving feed digestibility and nutrient metabolism [40]. RAS and Integrated Multi-trophic Aquaculture (IMTA) can significantly reduce dissolved inorganic nitrogen and phosphorus by using macroalgae [41]. To enhance oxygenation, absorb carbon dioxide and transform waste streams into beneficial co-products, microalgae have recently been added to RAS [33]. Two nutritional techniques that have been demonstrated to be effective in reducing waste outputs are the use of feed additives and feed formulation optimization [40]. When combined with innovative system designs and waste treatment methods, these tactics provide practical means of improving nutrient utilization and cutting waste in RAS operations.

Biofiltration and Nutrient Cycling in RAS

Biofiltration and nutrient cycling in recirculating aquaculture systems (RAS) involve complex microbial communities and a variety of treatment approaches. Both bacterial and plant-based biofilms can efficiently remove nutrients; bacterial filters are especially effective at eliminating ammonia and nitrite, while plant filters are more effective at eliminating phosphate and nitrate [42]. RAS biofilters contain a range of bacterial taxa, with comammox Nitrospira and ammonia-oxidizing archaea playing a significant role in nitrification [43]. Maintaining water quality requires removing nutrients from RAS, which can be done in a variety of ways, including mechanical and biological filtration [44]. RAS and Integrated Multi-trophic Aquaculture (IMTA) can optimize nutrient utilization by recycling aquaculture waste. RAS and macroalgae IMTA together can significantly reduce dissolved inorganic nitrogen and phosphorus, which could improve aquaculture's sustainability, per a dynamic nutrient mass balance model [41].

Role of Probiotics and Enzymes in Feed Optimization

Enzymes and probiotics are essential for maximizing feed utilization and enhancing water quality in aquaculture systems, such as recirculating aquaculture systems (RAS). By generating digestive enzymes and short-chain fatty acids, probiotics improve feed digestibility and support gut health and nutrient absorption [45]. For plant-based diets high in anti-nutritional factors, enzyme supplementation, especially phytase and xylanase, improves nutrient digestibility and retention [46].

In fish such as Nile tilapia, the combination of probiotics and enzymes can improve nutrient utilization, feed conversion ratio and growth performance [46]. These supplements also have a positive impact on microbial interactions and the diversity of the gut microbiome [46]. Probiotics, prebiotics, amino acids and natural sorbents work together in RAS to normalize water parameters, decrease bacterial pollution and speed up fish growth [47]. These results demonstrate the potential of enzymes and probiotics to enhance feed optimization and overall aquaculture productivity.

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Challenges and Solutions in Feed Management in RAS

Feed management in Recirculating Aquaculture Systems (RAS) offers many difficulties, especially because of the complexity of balancing optimal fish growth with maintaining water quality. Feed waste is one of the main problems; uneaten feed and fish excretion build up, so overloading the system with organic material. Ammonia and nitrite levels may rise as a result, which would strain biofiltration systems and finally compromise water quality [12]. Moreover, the different nutritional needs of various species, life stages and feeding habits make it more difficult to create a uniform feeding plan that is economical and effective. Poor feed conversion can result from insufficient feeding practices, which not only compromise the health and growth of the fish but also increase operational costs for the aquaculture system.

Precision feeding techniques have proven to be a successful way to maximize feed use and cut waste to solve these problems. Advanced technologies including automated feeding systems, real-time monitoring of fish feeding behavior and sensors tracking water quality parameters let more precise feed delivery tailored to the fish's metabolic needs. High-quality, easily digestible feeds also help to reduce waste by guaranteeing fish absorb the most nutrients from the feed, therefore maximizing nutrient absorption. Including plant-based proteins and functional additives like probiotics among other feed components has also been demonstrated to improve feed efficiency and fish health while lowering environmental effect [10]. Combining these technologies will help aquaculture systems to greatly improve feed management, therefore enabling more sustainable and economically feasible RAS operations.

Future Trends in Feed Strategy and Management in RAS

Sustainability issues and the need for reasonably priced production techniques are increasingly shaping feed strategy and management in Recirculating Aquaculture Systems (RAS). Increasing interest in alternative feed sources that reduce dependence on marine and terrestrial resources is seen as the aquaculture sector under pressure to lower its environmental impact. Prominent substitutes are plant-based proteins, insect meals and microbial-based feeds, which help to lower the ecological effect of fish farming [48]. Alongside this, technologies such as biofloc, bio-RAS and integrated multitrophic aquaculture (IMTA) are emerging as circular bioeconomy solutions, cutting inputs and reusing waste. These systems support sustainable practices by encouraging nutrient cycling and water purification via varied microbial populations and they fit the trend of urban agriculture emphasizing local production and consumption [49].

Despite the progress, there are still issues with optimizing these systems, especially when it comes to controlling microbial populations and preserving water quality. Problems like off-flavor-producing microorganisms can affect the quality of farmed fish and the equilibrium between heterotrophic and nitrifying bacteria is essential for efficient nutrient cycling [50]. More research into sustainable feed ingredients and precision feeding technologies will be crucial as RAS systems grow and intensify to meet the growing demand for seafood worldwide. These developments will be crucial for raising overall system sustainability, cutting waste and increasing feed efficiency. Further technological developments will be necessary for aquaculture in the future to solve environmental issues and guarantee that feed management techniques are effective and robust in the face of demands for global food security [51].

Conclusion

In conclusion, maximizing fish growth, guaranteeing system sustainability and reducing environmental impact all depend on efficient feed management in recirculating aquaculture systems (RAS). The significance of choosing premium, easily digested feeds that satisfy the unique nutritional requirements of cultured species is one of the discussion's main conclusions. In addition to alternative feed sources like plant-based proteins and insect meals, precision feeding technologies hold great promise for increasing feed efficiency and lowering dependency on conventional marine-based resources. Additionally, both economic viability and environmental sustainability depend on controlling the Feed Conversion Ratio (FCR) and reducing waste through sophisticated feed strategies.

Future studies should focus on developing precision feeding systems, finding new sustainable feed ingredients and enhancing the bioavailability of substitute proteins. Fish health, feed utilization and disease resistance may all be improved by research into functional feeds, such as probiotics and immunostimulants. The development of integrated and sustainable feed strategies that can satisfy the expanding global demand for seafood while reducing environmental impact will also require interdisciplinary research combining aquaculture, environmental science and biotechnology. Aquaculture can become more productive and ecologically conscious by tackling these issues and keeping up with feed management innovations.

References

1. Nazar AK, Jayakumar R, Tamilmani G. Recirculating aquaculture systems. Environmental Science. CMFRI Manual Customized Training Book. 2013.
2. Espinal CA, Matulić D. Recirculating aquaculture technologies. In: Aquaponics food production systems: Combined aquaculture and hydroponic production technologies for the future. Springer. 2020. Available from: https://doi.org/10.1007/978-3-030-15943-6
3. Jacinda AK, Yustiati A andriani Y. Recirculating aquaculture system (RAS) technology applications in Indonesia: A review. Jurnal Perikanan dan Kelautan. 2021;11(1):43–59.
4. Li H, Cui Z, Cui H, Bai Y, Yin Z, Qu K. A review of influencing factors on a recirculating aquaculture system: Environmental conditions, feeding strategies and disinfection methods. J World Aquac Soc 2023; 54(3):566–602. Available from: https://doi.org/10.1111/jwas.12976
5. Owatari MS, Mouriño JLP. Practical and essential information on water reuse systems in experimental aquaculture production: A descriptive review. J Aquac Fish Sci 2020; 3(1):186–202. Available from: https://doi.org/10.1007/978-3-030-15943-6_3
6. Kırkpınar F, Açıkgöz Z. Feeding. In: Animal husbandry and nutrition. IntechOpen 2018. Available from: https://doi.org/10.5772/intechopen.78618
7. Yakupitage A. On-farm feeding and feed management strategies in tropical aquaculture. In: Hasan MR, New MB, editors. On-farm feeding and feed management in aquaculture. FAO Fisheries and Aquaculture Technical Paper, FAO; 2013, 583.
8. Assis YP, Porto LD, Melo N, Palheta GD, Luz RK, Favero GC. Feed restriction as a feeding management strategy in Colossoma macropomum juveniles under recirculating aquaculture system (RAS). Aquaculture 2020; 529:735689.
9. Gatlin DM. Principles of fish nutrition. SRAC Publication. 2010;5003.
10. Prabu E, Felix S, Felix N, Ahilan B, Ruby P. An overview on significance of fish nutrition in aquaculture industry. Int J Fish Aquat Stud 2017;5 (6):349–355.

11. Webster CD, Lim C. Nutrition requirement and feeding finfish for aquaculture. CABI Publishing. 2002.
12. Piedrahita RH. Reducing the potential environmental impact of tank aquaculture effluents through intensification and recirculation. Aquaculture 2003; 226(1–4): 35-44. https://doi.org/10.1016/S0044-8486(03)00465-4
13. Akter M, Schrama JW, Adhikary U, Alam MS, Mamun-Ur-Rashid M *et al*. Effect of pellet-size on fish growth, feeding behaviour and natural food web in pond polyculture. Aquaculture 2024; 593:1–9. https://doi.org/10.1016/j.aquaculture.2024.06.001
14. Shipton TA, Hasan MR. An overview of the current status of feed management practices. In Hasan MR, New MB, editors. On-farm feeding and feed management in aquaculture. FAO Fisheries and Aquaculture Technical Paper, FAO;2013, 583.
15. Tacon AGJ, Hasan MR. Global synthesis of feeds and nutrients for sustainable aquaculture development. Study and analysis of feeds and fertilizers for sustainable aquaculture development. FAO Fisheries Technical Paper, FAO; 2007. 497.
16. Barrows FT, Stone DAJ, Hardy RW. The effects of extrusion on nutritional value of soybean meal for rainbow trout (Oncorhynchus mykiss). Aquaculture 2008; 283(1–4): 148-155, 2008, https://doi.org/10.1016/j.aquaculture.2007.01.017
17. Dhont J, Van Stappen G. Biology, tank production and nutritional value of Artemia. In Live feeds in marine aquaculture 2003; 79-106.
18. Sun G, Liu Y, Denggao Q, Yi M, Li X, Li Y. Effects of feeding rate and frequency on growth performance, digestion and nutrients balances of Atlantic salmon (*Salmo salar*) in recirculating aquaculture systems (RAS). Aquaculture Research 2016; 47: 176-188.
19. Pěnka T, Malinovskyi O, Imentai A, Kolářová J, Kučera V, Policar T. Evaluation of different feeding frequencies in RAS-based juvenile pikeperch (*Sander lucioperca*) aquaculture. Aquaculture 2023; 562: 1-8. https://doi.org/10.1016/j.aquaculture.2023.739335
20. Petrea SM, Mogodan A, Simionov IA, Cristea V. Effect of feeding rate on growth performance of *A. stellatus* (Pallas, 1771) reared in a recirculating aquaculture system. Scientific Papers-Animal Science Series: Lucrări

Ştiinţifice - Seria Zootehnie 2019; 72: 1-8.

21. Godoy-Olmos S, Jauralde I, Monge-Ortiz R, Milián-Sorribes MC, Jover-Cerdá M, Tomás-Vidal A *et al*. Influence of diet and feeding strategy on the performance of nitrifying trickling filter, oxygen consumption and ammonia excretion of gilthead sea bream (*Sparus aurata*) raised in recirculating aquaculture system. Aquaculture International 2022; 30:581–606. https://doi.org/10.1007/s10499-021-00821-3
22. Huang M, Zhou YG, Yang XG, Gao QF, Chen YN, Ren YC *et al*. Optimizing feeding frequencies in fish: A meta-analysis and machine learning approach. Aquaculture 2025; 595(2):1–9. Https://doi.org/10.1016/j.aquaculture.2025.738321
23. Santos RRV, Viana JS, Rocha LF, Rocha LMO, Vieitas BCP, Costa BGB. Feeding frequency of juvenile tambaqui (Colossoma macropomum) reared in a recirculation system. Acta Of Fisheries and Aquatic Resources 2022; 10(1):67–73. https://doi.org/10.46732/actafish.2022.10.1.67-73
24. Hall SG, Frinsko MO. Automation in marine larviculture. In: 2021 ASABE Annual International Virtual Meeting, Jul 12–16, 2021.
25. Wang Y, Yu X, Liu J, An D, Wei Y. Dynamic feeding method for aquaculture fish using multi-task neural network. Aquaculture 2022; 551:737913.
26. Yeoh SJ, Taip FS, Endan JB, Talib RA, Mazlina MK. Development of automatic feeding machines for aquaculture industry. Pertanika J Sci Technol 2010; 18:105–110.
27. Kishore KK, Krishna PV, Srikanth D. Automatic Feeding system for Aquaculture. Third International Conference on Sensing, Signal Processing and Security (ICSSS) 2017;426–429.
28. Romli MA, Daud S, Zainol SM, Kan PL, Ahmad ZA. Automatic RAS data acquisition and processing system using fog computing. 2017 IEEE 13th Malaysia International Conference on Communications (MICC) 2017;229–234.
29. Ye Z, Zhao J, Han Z, Zhu S, Li J, Lu H *et al*. Behavioral Characteristics and Statistics-Based Imaging Techniques in the Assessment and Optimization of Tilapia Feeding in a Recirculating Aquaculture System. Trans ASABE 2016; 59:345–355. https://doi.org/10.13031/TRANS.59.11406

30. Dalila N, Abdullah K, Kamarudin N, Ayu N, Masuri N, Natasha N *et al*. Smart Feeder Monitoring Devices with Mobile Application. J Design for Sustainable and Environment 2019;1(1):1–4.

31. Chiu CC, Liao TL, Chen CH, Kao SE. AIoT precision feeding management system. Electronics 2022; 11(20):3358. Available from: https://doi.org/10.3390/electronics11203358

32. AlZu'bi HS, Al-Nuaimy W, Buckley J, Young IS. An intelligent behavior-based fish feeding system. 2016 13th International Multi-Conference on Systems, Signals & Devices (SSD) 2016;22–29. https://doi.org/10.1109/SSD.2016.7473754

33. Ende SS, Henjes J, Spiller M, Elshobary ME, Hanelt D, Abomohra AE. Recent advances in recirculating aquaculture systems and role of microalgae to close system loop. Bioresour Technol 2024; 407:131107. https://doi.org/10.1016/j.biortech.2024.131107

34. Helberg GA, Anichini M, Kolarevic J, Sæther B, Noble C. Soundscape characteristics of RAS tanks holding Atlantic salmon (*Salmo salar*) during feeding and feed withdrawal. Aquaculture 2024; 593:741325.

35. Martins CI, Eding EH, Verreth JA. Stressing fish in Recirculating Aquaculture Systems (RAS): Does stress induced in one group of fish affect the feeding motivation of other fish sharing the same RAS? Aquac Res 2011; 42:1378–1384.

36. Mohammed F, Gabbadon P, Ajmal T, Goodchild MS. A study on the effect of feed load on mortality of Pacific white shrimp Litopenaeus vannamei. Aqua Fish Fish 2024; 4:e187.

37. Gołaś I, Szmyt M, Potorski J, Łopata M, Gotkowska-Płachta A, Glińska-Lewczuk K. Distribution of *Pseudomonas fluorescens* and *Aeromonas hydrophila* Bacteria in a Recirculating Aquaculture System during Farming of European Grayling (*Thymallus thymallus L.*) Broodstock. Water 2019; 11:376. https://doi.org/10.3390/w11020376

38. Flo VO, Cavrois-Rogacki T, Hansen JO, Vigen J, Gitlesen T, Lekang OI. RAS-Designed Diets Result in Lower Accumulation of Nitrogen, Phosphorus and Zinc in Recirculating Aquaculture System Compared with Traditional Flow-Through Designed Diets. Fishes 2024; 9(8):300. https://doi.org/10.3390/fishes9080300

39. Mongirdas V, Žibienė G, Žibas A. Waste and its characterization in closed

recirculating aquaculture systems – a review. J Water Secur 2017; 3(1). https://doi.org/10.15544/jws.2017.002

40. Bureau D, Hua K. Towards effective nutritional management of waste outputs in aquaculture, with particular reference to salmonid aquaculture operations. Aquac Res 2010; 41(5):777–792. https://doi.org/10.1111/j.1365-2109.2009.02431.x
41. Qiu X, Carter C, Hilder PE, Hadley S. A dynamic nutrient mass balance model for optimizing waste treatment in ras and associated imta system. Aquaculture 2022; 555:738216. https://doi.org/10.1016/j.aquaculture.2022.738216
42. Irhayyim T, Beliczky G, Bercsényi M. Nutrient bioremediation efficiency of bacterial biofilms and plant-based biofilters in a recirculating common carp (*Cyprinus carpio L.)* culture system. Iran J Fish Sci 2021; 20(3):828–845. https://doi.org/10.22092/ijfs.2021.124132
43. Bartelme RP, McLellan SL, Newton RJ. Freshwater recirculating aquaculture system operations drive biofilter bacterial community shifts around a stable nitrifying consortium of ammonia-oxidizing archaea and comammox nitrospira. Front Microbiol 2017; 8. https://doi.org/10.3389/fmicb.2017.00101
44. Pratiwy FM. The Overview of Utilization of Nutrient Removal in Recirculating. Glob Sci J 2020; 8(5).
45. Allameh SK, Noaman V, Boroumand-Jazi M, Ganjour M, Nahavandi R, Kamaleddin S. Some Beneficial Effects of Probiotics in Aquaculture. J Clin Trials Res 2021; 4(1):215–218.
46. Maas RM, Verdegem M, Debnath S, Marchal L, Schrama J. Effect of enzymes (phytase and xylanase), probiotics (*B. amyloliquefaciens*) and their combination on growth performance and nutrient utilisation in Nile tilapia. Aquaculture 2021; 533:736226. https://doi.org/10.1016/j.aquaculture.2020.736226
47. Romanova EM, Romanov VV, Lyubomirova VN, Shadieva LA, Shlenkina TM. Vectors for the development of high-tech industrial aquaculture. BIO Web Conf 2020; 27:00132. https://doi.org/10.1051/bioconf/20202700132
48. Schalekamp D, Hill KV, Huisman Y. A Horizon Scan on Aquaculture 2015: Fish Feed. Agric Food Sci Environ Sci 2016.

49. Zimmermann S, Kiessling A, Zhang J. The future of intensive tilapia production and the circular bioeconomy without effluents: biofloc technology, recirculation aquaculture systems, bio-RAS, partitioned aquaculture systems and integrated multitrophic aquaculture. Rev Aquac 2023; 15(S1):22–31. https://doi.org/10.1111/raq.12744

50. Rurangwa E, Verdegem M. Microorganisms in recirculating aquaculture systems and their management. Rev Aquac 2014; 7(2):117–130. https://doi.org/10.1111/raq.12057

51. Bostock J, McAndrew BJ, Richards RH, Jauncey K, Telfer TC, Lorenzen K *et al*. Aquaculture: global status and trends. Philos Trans R Soc Lond B Biol Sci 2010; 365(1554):2897–2912. https://doi.org/10.1098/rstb.2010.0170

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4

CHAPTER

Optimizing Aquaculture: Comparative Insights into Fish Growth and Feed Efficiency in RAS and Traditional Pond Systems

Titin Kurniasih
Research Center for Freshwater Aquaculture, National Research and Innovation Agency (BRIN), Indonesia

Novita Panigoro*
Research Center for Freshwater Aquaculture, National Research and Innovation Agency (BRIN), Indonesia

Ediwarman
Research Center for Freshwater Aquaculture, National Research and Innovation Agency (BRIN), Indonesia

Waryat
Research Center of Agroindustry, National Research and Innovation Agency (BRIN), Indonesia

Corresponding Author: novi046@brin.go.id

Abstract

This chapter explores the comparative performance of Recirculating Aquaculture Systems (RAS) and traditional pond systems in optimizing fish growth and feed efficiency, two key factors influencing aquaculture productivity and sustainability. RAS provides a controlled and stable environment by regulating water quality, temperature, pH and dissolved oxygen, enabling higher specific growth rates (SGR) and lower feed conversion ratios (FCR). In contrast, traditional pond systems rely on natural conditions, which are subject to environmental fluctuations, waste accumulation and limited control over key parameters—often resulting in slower growth and higher feed requirements. The analysis highlights the advantages of RAS in supporting higher stocking densities, reducing fish stress and maximizing feed utilization. Furthermore, innovations such as biofloc and aquaponic integrations within RAS are discussed for their potential to further enhance feed efficiency and sustainability. The findings provide clear evidence that RAS holds a superior position in delivering consistent performance and resource efficiency, offering valuable insights for researchers, practitioners and policymakers committed to advancing sustainable aquaculture systems.

Keywords: RAS, traditional pond systems, SGR, FCR, sustainable aquaculture.

Introduction

Aquaculture has emerged as a key pillar of global food production, responding to the increasing demand for sustainable protein sources [1, 2]. As this sector expands, the optimization of production efficiency and environmental sustainability becomes increasingly critical. Central to this pursuit is the comparison between Recirculating Aquaculture Systems (RAS) and traditional pond systems—two widely used but fundamentally different approaches in fish farming.

RAS represents a modern, closed-loop system that emphasizes control and precision. It enables aquaculturists to manage water quality, temperature and dissolved oxygen and pH levels with high accuracy, creating a stable and optimal environment for fish growth. In contrast, traditional pond systems rely heavily on natural processes and are vulnerable to environmental fluctuations [3-5], which can hinder fish performance and compromise production efficiency.

One of the most significant advantages of RAS is its ability to maintain excellent water quality. Ammonia, a toxic byproduct of fish metabolism, is effectively removed in RAS via biological filtration systems that convert it into less harmful compounds. This process, along with advanced aeration technologies, ensures that fish are kept in low-stress, oxygen-rich conditions supporting faster growth and improved health [6-8]. Traditional ponds, however, often suffer from waste accumulation and inconsistent oxygen levels, particularly under high stocking densities [9].

Environmental stability in RAS extends to temperature and pH regulation, both of which significantly influence fish metabolism. By keeping temperature within species-specific optimal ranges such as 24-28°C for tilapia—RAS ensures efficient nutrient utilization and protein synthesis [10]. In contrast, traditional ponds are susceptible to diurnal and seasonal changes that can stress fish, reduce appetite and lower growth performance [11].

Stocking density is another area where RAS demonstrates superiority.

The system's tight environmental control allows for higher densities without sacrificing fish welfare. This leads to more efficient space usage and greater biomass yield. Conversely, traditional ponds are limited by their natural capacity to maintain water quality and overcrowding often results in increased competition and disease risk [12].

These environmental and operational differences significantly affect key performance metrics such as the Specific Growth Rate (SGR) and Feed Conversion Ratio (FCR). SGR is consistently higher in RAS due to reduced environmental stress and optimized growth conditions [13, 14]. Similarly, FCR is lower in RAS, indicating more efficient feed utilization—a direct result of stable environmental parameters and advanced feed management [15].

While traditional pond systems remain important, particularly in low-resource settings, the performance advantages offered by RAS position it as a forward-looking solution in sustainable aquaculture. Understanding these differences in biological outcomes and system efficiencies is vital for researchers, practitioners and policymakers aiming to enhance aquaculture productivity while minimizing environmental impact.

RAS and Traditional Pond Systems: Environmental Comparison

In the context of modern aquaculture, the environmental conditions in which fish are raised play a crucial role in their growth performance and overall health [16-18]. Recirculating Aquaculture Systems (RAS) offer a controlled environment with significant advantages over traditional pond systems in terms of water quality management, temperature and pH control and stocking density management. This section compares these two aquaculture systems by examining how they manage key environmental factors that influence the specific growth rate (SGR) and feed conversion ratio (FCR) of fish.

One of the defining features of RAS is its ability to tightly control water quality, particularly with regard to nitrogenous waste and dissolved oxygen (DO) levels. Nitrogenous waste, primarily ammonia excreted by fish, is a critical factor that affects water quality in both RAS and traditional pond systems. Ammonia is toxic at high concentrations and must be efficiently removed or converted to less harmful compounds [7, 19]. In RAS, ammonia is converted into nitrites and then to nitrates through a biological filtration process involving nitrifying bacteria [8]. This conversion process ensures that the water remains free of toxic nitrogen compounds, thus supporting better fish health and growth.

Furthermore, RAS systems maintain optimal levels of dissolved oxygen, which is essential for fish metabolism and aerobic respiration. By employing advanced aeration technologies, such as microbubble systems, RAS can ensure that DO levels remain consistently above the minimum required for fish, even in densely stocked systems [8]. This stable oxygenation, in turn, enhances growth rates and overall fish performance by providing an environment that supports efficient metabolism and energy use [20, 21].

In contrast, traditional pond systems face significant challenges with water quality management, particularly when it comes to nitrogenous waste and oxygen levels. In these open systems, water quality can vary widely depending on external factors such as weather, feed regimes and stocking densities. Ammonia and other nitrogenous compounds tend to accumulate in ponds, especially in high-density settings where fish excrete large amounts of waste. Without effective filtration or waste removal systems, these compounds can reach toxic levels, leading to poor fish health, stunted growth and, in some cases, increased mortality [9]. Additionally, traditional pond systems often lack efficient aeration, which results in fluctuating oxygen levels. Inadequate oxygen supply, especially during periods of high biomass or organic decomposition, can stress fish and reduce their growth efficiency [11]. Therefore, the inability to consistently control water quality in traditional systems leads to greater variability in growth rates, as fish are subjected to intermittent stress caused by poor water quality.

RAS offers superior control over temperature and pH, two critical environmental factors that directly influence metabolic rates and overall fish growth. Fish are ectothermic organisms, meaning their body temperature is influenced by the surrounding water temperature [22]. Each fish species has a specific temperature range in which it grows most efficiently and deviations from this range can result in stress, reduced growth and increased suscep tibility to disease [23]. RAS systems allow for the precise control of water temperature, ensuring that it remains within the optimal range for the fish species being cultured [10]. For instance, tilapia, which are commonly cultured in RAS, thrive at temperatures between 24°C and 28°C [24]. By maintaining water temperature within this range, RAS supports optimal metabolic efficiency and protein synthesis, leading to improved growth rates.

Similarly, pH levels in RAS systems are tightly controlled. Fish are sensitive to pH fluctuations and deviations from the optimal range can impair fish health and growth [25]. In RAS, pH is monitored and adjusted as necessary to ensure that it remains within the ideal range for the species being cultured.

This stability in both temperature and pH promotes optimal metabolic conditions and minimizes stress, leading to superior growth performance.

In traditional pond systems, temperature and pH conditions are subject to natural fluctuations. Water temperature in ponds can vary significantly throughout the day and across seasons. For instance, during the daytime, temperatures may rise, while at night, they can drop, creating a diurnal temperature variation that can be stressful for fish [11]. In warmer climates, such temperature fluctuations can increase the metabolic rate of fish, leading to higher energy expenditure and reduced growth efficiency. During colder seasons, low temperatures can slow down metabolism and impair fish growth.

Similarly, pH levels in traditional ponds can be influenced by factors such as photosynthetic activity, organic decomposition and the composition of the pond water. In ponds with high organic matter, pH can fluctuate rapidly, particularly at night when oxygen levels are low and carbon dioxide accumulates, lowering the pH. Such fluctuations can lead to suboptimal growth conditions, especially in sensitive species. Therefore, the lack of precise control over temperature and pH in traditional pond systems often leads to environmental stress, resulting in slowed growth and inefficient feed conversion.

One of the key advantages of RAS is its ability to support higher stocking densities without compromising water quality. The closed-loop nature of RAS allows for precise monitoring and control of water parameters, such as oxygen levels and waste concentration, which can otherwise be compromised in more densely stocked systems. In RAS, high-density stocking can be achieved without the negative consequences typically associated with overcrowding, such as increased disease risk and reduced growth rates. Studies have shown that RAS systems can maintain optimal growth conditions for fish even at higher stocking densities, leading to higher biomass yields and more efficient use of space [26].

Moreover, the ability to regulate stocking density in RAS contributes to better resource utilization and enhanced production efficiency. By avoiding overcrowding and ensuring that fish have access to adequate oxygen and nutrients, RAS enables faster growth and more efficient feed conversion, ultimately improving profitability for aquaculture producers.

In contrast, traditional pond systems often face challenges related to overcrowding. Overpopulation in ponds can lead to increased competition for food, space and oxygen. As stocking densities increase, the availability of resources for each fish decreases, resulting in slower growth rates and higher susceptibility to diseases. The competition for oxygen in overcrowded ponds, coupled with the accumulation of waste products, further exacerbates the stress on fish, slowing their metabolic rates and reducing growth efficiency [12].

In many traditional pond systems, stocking density is limited by the natural ability of the pond to maintain water quality. When stocking densities exceed the pond's capacity to process waste and maintain oxygen levels, fish growth is impaired, leading to suboptimal feed conversion and overall lower production efficiency [27].

Specific Growth Rate (SGR) in Recirculating and Conventional Aquaculture Systems

Specific Growth Rate (SGR) is a critical metric in aquaculture and is defined as the percentage increase in fish weight per unit of time. SGR is an important metric in aquaculture as it reflects the efficiency of fish growth, providing insight into the overall health, metabolic function and performance of the fish. A higher SGR indicates that fish are growing faster, which translates to more efficient use of resources such as feed, space and water. In aquaculture systems, optimizing SGR is a major goal, as it directly impacts both production costs and profitability.

SGR is essential in evaluating the success of different aquaculture systems and serves as a key indicator of the health and productivity of fish in these systems. A higher SGR reflects superior growth, which is crucial for achieving efficient production in aquaculture. This section compares the SGR of fish raised in Recirculating Aquaculture Systems (RAS) and traditional pond systems, highlighting the advantages of RAS in optimizing growth conditions.

In comparing RAS and traditional pond systems, the SGR of fish can be influenced by various environmental factors, including water quality, temperature, stocking density and nutrient availability. These factors contribute to the conditions that either promote or hinder fish growth. Thus, evaluating the SGR of fish in these two systems provides valuable insights into their relative efficiencies in aquaculture production.

RAS provides a controlled environment where key environmental factors, such as oxygen levels, temperature and nutrient availability, are meticulously optimized to promote fish growth. In RAS, dissolved oxygen levels are maintained consistently high, often exceeding the minimum requirements for various fish species. This stable oxygenation plays a crucial role in supporting aerobic metabolism, which is essential for fast growth [13]. The ability to control oxygen levels continuously enhances fish health and ensures that growth rates remain high, which ultimately improves SGR.

Temperature regulation is another key advantage of RAS. In RAS, water temperature is carefully monitored and adjusted to ensure that it remains within the optimal range for the specific fish species being cultivated. For instance, tilapia grow optimally within a temperature range of 24°C to 28°C and maintaining this range in RAS environments ensures optimal metabolic function and growth [28]. This level of control is not possible in traditional pond systems, where temperature fluctuations due to external weather conditions can cause stress and negatively impact growth.

Furthermore, RAS allows for the continuous recycling and filtering of water, ensuring that nutrients remain available for the fish throughout their growth cycle. Biofiltration processes remove waste products and excess nutrients, maintaining high water quality and preventing the accumulation of toxic substances like ammonia, which can hinder growth [29]. These features make RAS a highly efficient system for enhancing fish growth and improving SGR.

Studies have consistently demonstrated the superior performance of fish grown in RAS compared to traditional pond systems. Research on species such as tilapia and African catfish has shown that these species exhibit significantly higher SGR when cultured in RAS environments. For example, in a study by [30], African catfish cultured in RAS environments showed a marked improvement in growth performance compared to those raised in traditional ponds. Similarly, tilapia raised in RAS environments have consistently demonstrated higher SGRs due to the controlled conditions and efficient nutrient management [14].

These case studies highlight the benefits of RAS in optimizing growth conditions, ultimately leading to faster growth rates, improved feed conversion and more efficient use of resources. RAS systems provide fish with an ideal environment for maximizing their genetic growth potential, making them a more sustainable and efficient option for modern aquaculture.

In contrast to RAS, traditional pond systems are more susceptible to fluctuations in environmental factors, which can lead to variability in growth rates and lower overall SGR. Traditional ponds rely on natural water sources and are influenced by external environmental conditions such as temperature, water quality and feed availability. These factors are often less controlled, resulting in an unpredictable environment for fish. In such systems, water quality is a major concern. For instance, ammonia and nitrites tend to accumulate in ponds, especially under high stocking densities and without efficient waste management, these compounds can reach toxic levels, impairing fish health and growth [9].

Water temperature in traditional ponds is also subject to natural fluctuations, which can vary significantly across the day and throughout the seasons. Such temperature variations can cause stress in fish, affecting their metabolic processes and slowing down growth [11]. These uncontrolled environmental conditions contribute to the variability in SGR observed in traditional pond systems.

External factors such as water quality fluctuations and food availability further exacerbate the variability in growth rates in traditional pond systems. Traditional ponds are often affected by poor water quality, especially during periods of high stocking density, which can lead to competition for oxygen and food. In such cases, fish are subjected to stress, which can reduce their metabolic rates and hinder growth. As water quality deteriorates, fish in traditional systems may experience reduced growth efficiency and even higher mortality rates [15].

Additionally, in traditional systems, feed availability is often influenced by external factors such as local feed supply and farmer management practices. Inconsistent feed quality and inadequate feeding strategies can result in suboptimal growth and lower SGR, as fish are not receiving the necessary nutrients to fuel their growth [31]. This lack of control over external factors, coupled with inconsistent feed management, leads to less predictable growth outcomes in traditional pond systems.

Overall, RAS consistently provides superior conditions for fish growth compared to traditional pond systems. By maintaining optimal levels of oxygen, temperature and nutrients, RAS reduces stress, enhances metabolic efficiency and ultimately promotes higher growth rates and better feed conversion. The ability to regulate water quality and stocking density in RAS allows for consistent and efficient fish growth, leading to improved SGR and overall aquaculture performance.

In contrast, traditional pond systems face significant challenges in controlling water quality, temperature and feeding regimes. These factors contribute to variability in growth rates, resulting in lower and less consistent SGR. While traditional systems are still widely used, especially in regions with limited access to advanced technologies, their growth potential is constrained by environmental variability and inefficient management practices.

Feed Conversion Ratio (FCR) in RAS and Traditional Aquaculture Systems

Feed Conversion Ratio (FCR) is a critical measure in aquaculture, reflecting the efficiency with which fish convert feed into body mass and is calculated as the ratio of feed consumed to the weight gained by the fish. A lower FCR indicates a more efficient conversion of feed into growth, making it an essential metric for evaluating the economic and environmental sustainability of aquaculture systems. This section will compare the FCR in Recirculating Aquaculture Systems (RAS) and traditional pond systems, focusing on how these systems manage feed and optimize growth efficiency. A lower FCR indicates better feed efficiency, as less feed is required to produce a given amount of fish biomass. In aquaculture, optimizing FCR is crucial for improving the economic viability and sustainability of fish farming. Efficient feed management reduces operational costs, minimizes feed waste and contributes to environmental sustainability by lowering the impact of feed production and waste disposal.

FCR can be influenced by various factors, including the quality of feed, water quality, stocking density and the overall management practices within the aquaculture system. This section will explore how RAS, with its controlled environment, provides significant advantages in terms of feed efficiency compared to traditional pond systems.

RAS provides a controlled environment where feed management can be precisely tailored to the needs of the fish. In these systems, the water quality, temperature and oxygen levels are continuously monitored and optimized, ensuring that fish can efficiently metabolize the feed they consume. This controlled environment minimizes stress and maximizes feed conversion, which results in improved FCR values [14].

One of the key advantages of RAS is its ability to provide fish with a consistent and predictable environment. For instance, by maintaining stable water quality and temperature, RAS ensures that fish experience minimal fluctuations in their metabolic rate, which is crucial for efficient feed utilization. Additionally, the use of high-quality, specially formulated feed in RAS systems allows for better nutrient absorption and conversion into body mass, leading to superior FCR [13].

In RAS, fish are also typically kept at higher densities than in traditional systems and the water quality is constantly recycled and filtered. This higher stocking density is possible due to the continuous monitoring and optimization of water parameters, including ammonia and dissolved oxygen levels, which reduces the risk of stress that could negatively impact feed conversion. With optimized water quality, fish are able to efficiently utilize the feed they consume, resulting in lower FCR [15].

In addition to the inherent advantages of RAS, biofloc and aquaponic systems further enhance feed conversion efficiency by providing additional nutrient sources. Biofloc systems utilize microorganisms, such as bacteria and algae, to process organic waste in the water, which can be consumed by the fish as an additional food source. This provides fish with supplemental nutrients and reduces the need for external feed inputs, improving overall feed efficiency [32]. Biofloc systems are particularly beneficial for species that can feed on these microorganisms, such as tilapia and shrimp, leading to improved growth and lower FCR.

Aquaponic systems, which combine fish farming with plant cultivation, also contribute to better feed conversion. In these systems, plants help absorb excess nutrients from the fish waste, thus maintaining water quality while providing fish with additional food sources. The integration of plants further reduces the amount of external feed required, as fish benefit from the nutrients that plants do not absorb [33]. This synergistic relationship between fish and plants in aquaponics enhances both fish growth and feed conversion, making RAS even more efficient in utilizing feed resources.

In contrast to RAS, traditional pond systems often exhibit poor feed efficiency due to a combination of resource competition, waste accumulation and suboptimal feeding strategies. In traditional systems, fish are raised in open ponds where feed is distributed, but the fish are often subject to uneven distribution of nutrients. Overcrowding, high stocking densities and competition for limited resources lead to inconsistent feed intake, which can reduce the efficiency of feed conversion and result in higher FCR values [12].

Moreover, the lack of precise control over water quality in traditional systems means that fish are often exposed to fluctuating oxygen levels, temperature changes and accumulating waste products. These factors can stress fish, reduce their feeding efficiency and slow down their growth rates. When water quality deteriorates, fish become less efficient at converting feed into biomass, resulting in higher FCR [11].

The management of feed in traditional pond systems is often less precise compared to RAS, leading to further inefficiencies in feed utilization. In many traditional systems, feeding strategies are based on visual observation rather than the careful monitoring of fish growth and feed intake. This can lead to either overfeeding or underfeeding, both of which negatively impact FCR. Overfeeding can lead to excess nutrients in the water, which can degrade water quality and increase the risk of disease, while underfeeding can result in suboptimal growth and higher feed conversion rates [31].

In traditional pond systems, water quality plays a crucial role in feed efficiency. Poor water quality, due to the accumulation of organic waste and nutrients, can stress fish and decrease their metabolic rate, making it harder for them to convert feed into body mass. Inadequate oxygen levels and fluctuating water temperatures further exacerbate this problem, making fish less efficient at utilizing feed [12]. The lack of advanced filtration or aeration systems in traditional ponds leads to inefficient waste removal, contributing to poor water quality and ultimately higher FCR.

Overall, RAS offers clear advantages over traditional pond systems in terms of feed conversion efficiency. In RAS, the ability to optimize water quality, temperature and oxygen levels ensures that fish can efficiently metabolize and convert feed into biomass, resulting in lower FCR. Additionally, the controlled environment in RAS reduces stress and competition for resources, leading to more consistent and higher feed conversion rates. The integration of biofloc and aquaponic systems further enhances feed efficiency by providing additional nutrient sources, reducing the reliance on external feed.

In contrast, traditional pond systems face significant challenges in managing feed efficiency due to poor water quality, overcrowding and inconsistent feed management. These factors contribute to higher FCR values, as fish in traditional systems are less efficient at converting feed into growth. The lack of control over environmental factors in traditional systems leads to increased stress and variability in growth, further exacerbating inefficiencies in feed conversion.

Conclusion

Recirculating Aquaculture Systems (RAS) offer superior environmental control, resulting in enhanced fish growth and feed efficiency compared to traditional pond systems. Through optimized water quality, temperature and stocking density, RAS consistently achieves lower FCR and higher SGR. These advantages highlight RAS as a promising pathway for sustainable, efficient and resilient aquaculture development in the future.

References

1. Luthada-Raswiswi R, Mukaratirwa S, O'Brien G. Animal protein sources as a substitute for fishmeal in aquaculture diets: a systematic review and meta-analysis. Applied Sciences 2021; 11(9): 3854. https://doi.org/10.3390/app11093854
2. Mugwanya M, Dawood M, Kimera F, Sewilam H. Replacement of fish meal with fermented plant proteins in the aquafeed industry: a systematic review and meta-analysis. Reviews in Aquaculture 2022; 15(1): 62-88. https://doi.org/10.1111/raq.12701
3. Tarunamulia T, Ratnawati E, Kamariah K, Asaf R, Athirah A. Factor affecting the willingness to adopt good aquaculture practices (gaps) in traditional shrimp farming in pinrang regency, south sulawesi province, indonesia. Bio Web of Conferences 2023;74: 06003. https://doi.org/10.1051/bioconf/20237406003
4. Fitriadi R, Palupi M, Setyawan A, Kusuma R, Nurhafid M. Isolation and molecular identification of proteolytic bacteria from vaname shrimp (lithopenaeus vannamei) ponds as probiotic agents. Iraqi Journal of Veterinary Sciences 2023; 37(1): 161-170. https://doi.org/10.33899/ijvs.2022.133468.2251
5. Duan Y, Liu L, Tang R, Xie S, Yang M, Zhang Z *et al*. Assessing changes in china's pond water quality from 1989 to 2020: implications for green development in aquaculture. Reviews in Aquaculture 2024; 17(1). https://doi.org/10.1111/raq.12997
6. Loh ZZ, Zaidi NS, Yong EL, Syafuddin A, Boopathy R, Kadier A. Current status and future research trends of biofiltration in wastewater treatment: a bibliometric review. Current Pollution Report 2022; 8; 234–248. https://doi.org/10.1007/s40726-022-00224-9
7. Mondal N, Kaur J, Ghosh A. Ammonia toxicity tolerance and behavioural

response in Zebrafish. Discover Toxicology 2025; **2**(13); 1-14. https://doi.org/10.1007/s44339-025-00028-8

8. Heriyati E, Rustadi R, Isnansetyo A, Triyatmo B, Istiqomah I, Deendarlianto D *et al*. Microbubble aeration in a recirculating aquaculture system (RAS) increased dissolved oxygen, fish culture performance and stress resistance of red tilapia (*Oreochromis* sp.). Trends in Sciences 2022; 19(20): 6251. https://doi.org/10.48048/tis.2022.6251
9. Auffret M, Yergeau É, Pilote A, Proulx É, Proulx D, Greer CW *et al*. Impact of water quality on the bacterial populations and off-flavours in recirculating aquaculture systems. Fems Microbiology Ecology 2013; 84(2): 235-247. https://doi.org/10.1111/1574-6941.12053
10. Atique F, Lindholm-Lehto P, Pirhonen J. Is aquaponics beneficial in terms of fish and plant growth and water quality in comparison to separate recirculating aquaculture and hydroponic systems?. Water 2022; 14(9): 1447. https://doi.org/10.3390/w14091447
11. Puspaningsih D, Setijaningsih L, Setiadi E, Taufik I. Effect of different stocking density of snakehead fish (Channa striata) cultured in recirculation aquaculture system. E3S Web of Conferences 2021; 322: 02005. https://doi.org/10.1051/e3sconf/202132202005
12. Li Z, Wang G, Yu E, Zhang K, Yu D, Gong W *et al*. Artificial substrata increase pond farming density of grass carp (Ctenopharyngodon idella) by increasing the bacteria that participate in nitrogen and phosphorus cycles in pond water. PeerJ 2019; 7:e7906. https://doi.org/10.7717/peerj.7906
13. Gichana Z, Liti D, Drexler S, Zollitsch W, Meulenbroek P, Wakibia J *et al*. Effects of aerated and non-aerated biofilters on effluent water treatment from a small-scale recirculating aquaculture system for Nile tilapia (Oreochromis niloticus L.). Die Bodenkultur Journal of Land Management Food and Environment 2019; 70(4): 209-219. https://doi.org/10.2478/boku-2019-0019.
14. Xiao M, Qian K, Wang Y, Bao F. Gc-ms metabolomics reveals metabolic differences of the farmed Mandarin fish Siniperca chuatsi in recirculating ponds aquaculture system and pond. Scientific Reports 2020; 10(1). https://doi.org/10.1038/s41598-020-63252-9
15. Rahmawati A, Supriatin F andayani S, Mubarok M, Rahman. Fish growth

performance in RAS pond using hydrocyclone mechanical filter. Jurnal Penelitian Pendidikan IPA 2024; 10(4): 2129-2135. https://doi.org/10.29303/jppipa.v10i4.6149

16. Kamiński R, Sikorska J, Polak-Juszczak L, Wolnicki J. Effects of temperature on body chemical composition and incidence of deformities in juvenile tench, tinca tinca (actinopterygii: cypriniformes: cyprinidae), fed a commercial dry diet and/or natural food. Acta Ichthyologica Et Piscatoria 2017; 47(1): 63-71. https://doi.org/10.3750/aiep/02074
17. Tumwesigye Z, Tumwesigye W, Opio F, Kemigabo C, Mujuni B. The effect of water quality on aquaculture productivity in ibanda district, uganda. Aquaculture Journal 2022; 2(1): 23-36. https://doi.org/10.3390/aquacj2010003
18. Mehrim A I and Refaey MM. An overview of the implication of climate change on fish farming in egypt. Sustainability 2023: 15(2): 1679. https://doi.org/10.3390/su15021679
19. Ramli NM, Verdegem MCJ, Yusoff FM, Zulkifely MK, Verreth JAJ. Removal of ammonium and nitrate in recirculating aquaculture systems by the epiphyte Stigeoclonium nanum immobilized in alginate beads. Aquaculture Environment Interaction 2017; 9:213-222 https://doi.org/10.3354/aei00225
20. Ruzzante S, Hoque R, Rahman MM, Bilton AM. A cross-over experiment for on-farm evaluation of a novel pond aquaculture aeration device. Aquaculture Research 2022; 53(17): 6343-6354. https://doi.org/10.1111/are.16108
21. Gui F, Sun H, Qu X, Niu S, Zhang G, Feng D. Temperature and dissolved oxygen lead to behavior and respiration changes in juvenile largemouth bass (micropterus salmoides) during transport. Fishes 2023; 8(12): 565. https://doi.org/10.3390/fishes8120565
22. Ramløy UB. Aspects of natural cold tolerance in ectothermic animals. Human Reproduction 2000; 15(5): 26-46. https://doi.org/10.1093/humrep/15.suppl_5.26
23. Chakrabarty J, Islam SMM, Hossain MN, Naziat A, Zahangir MM, Shahjahan M. Temperature-induced expression dynamics for the stress, appetite and growth-related genes in Nile tilapia (*Oreochromis niloticus*). Journal of Applied Ichthyology 2025;5475569: 14.

https://doi.org/10.1155/jai/5475569

24. Dey BK, Verdegem MCJ, Nederlof MAJ, Masagounder K, Mas-Muñoz J, Schrama JW. Effect of temperature on the energy utilization efficiencies of digested protein, fat and carbohydrates in Nile tilapia (*Oreochromis niloticus*). Aquaculture 2023; 576: 739876. https://doi.org/10.1016/j.aquaculture.2023.739876

25. Muhaimin M, Meliyani P, Kurnia D. Determination of Temperature, pH, Salinity, Dissolved Oxygen, TDS, TSS and Nitrite Content in 42-Day-Old Shrimp Farming Ponds. JKPK (Jurnal Kimia dan Pendidikan Kimia) 2024; 9(3): 550-563. doi:http://dx.doi.org/10.20961/jkpk.v9i3.93793

26. Li D, Liu Z, Xie C. Effect of stocking density on growth and serum concentrations of thyroid hormones and cortisol in Amur sturgeon, *Acipenser schrenckii*. Fish Physiology and Biochemistry 2012; 38(2): 511-520. https://doi.org/10.1007/s10695-011-9531-y

27. Abd El-Hack ME, El-Saadony MT, Nader MM, Salem HM, El-Tahan AM, Soliman SM *et al*. Effect of environmental factors on growth performance of Nile tilapia (Oreochromis niloticus). Int J Biometeorol 2022; 66(11):2183-2194. doi: 10.1007/s00484-022-02347-6.

28. Abbink W, Garcia A, Roques J, Partridge G, Kloet K, Schneider O. The effect of temperature and pH on the growth and physiological response of juvenile yellowtail kingfish S*eriola lalandi* in recirculating aquaculture systems. Aquaculture 2012; 330-333, 130-135. https://doi.org/10.1016/j.aquaculture.2011.11.043

29. Pachaiappan R, Cornejo-Ponce L, Rajendran R, Manavalan K, Femilaa Rajan V, Awad F. A review on biofiltration techniques: recent advancements in the removal of volatile organic compounds and heavy metals in the treatment of polluted water. Bioengineered 2022;13(4):8432-8477. DOI: 10.1080/21655979.2022.2050538.

30. Clols-Fuentes J, Nguinkal JA, Unger P, Kreikemeyer B, Palm HW. Bacterial community in African catfish (*Clarias gariepinus*) recirculating aquaculture systems under different stocking densities. Frontiers in Marine Science 2023; 10. https://doi.org/10.3389/fmars.2023.1073250

31. Makori AJ, Abuom PO, Kapiyo R, Anyona D, Dida G. Effects of water physico-chemical parameters on tilapia (*Oreochromis niloticus*) growth in earthen ponds in Teso North Sub-County, Busia County. Fisheries and

Aquatic Sciences 2017; 20(1). https://doi.org/10.1186/s41240-017-0075-7

32. Emerenciano MGC, Slinger J, Koster G, Aland J, Lima PC, Arsic M *et al*. Mineral supplementation in Jade Perch (*Scortum barcoo*) aquaponics with lettuce: a comparison with hydroponics and RAS. Animals 2025; 15(3): 317. https://doi.org/10.3390/ani15030317

33. Goddek S, Espinal CA, Delaide B, Jijakli MH, Schmautz Z, Wuertz S, *et al*. Navigating towards decoupled aquaponic systems: a system dynamics design approach. Water 2016; 8(7): 303. https://doi.org/10.3390/w8070303

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5

CHAPTER

Application of Humic Substance as Water Additive in Recirculating Aquaculture Systems

Rasidi*, Idil Ardi, Dewi Puspaningsih, Wahyu Pamungkas, Bastiar Nur, Kukuh Adiyana and Eri Setiadi
National Research and Innovation Agency, Cibinong Science Center, Cibinong, Nanggewer Mekar, Bogor, West Java, 1692, Indonesia

Lila Gardenia
Directorate of Scientific Collection Management, National Research and Innovation Agency Cibinong Science Center Cibinong, Nanggewer Mekar, Bogor, West Java, 1692, Indonesia

Achmad Suhermanto
Polytechnic Marine and Fisheries of Karawang, Marine and Fisheries Affairs Republic of Indonesia

Eko Setio Wibowo
Faculty of Biology, University of Jenderal Soedirman, Purwokerto, Central Java, Indonesia

Corresponding Author: rasi003@brin.go.id

Abstract

Humic substances (HS), originating from the decomposition of organic materials, have become acceptable natural improvements in recirculating aquaculture systems (RAS) due to their numerous biological and environmental benefits. This study examines the use of HS as a water addition, emphasizing its capacity to improve water quality, fish health and system sustainability. Evidence suggests that HS enhances nitrogen removal efficiency by promoting microbial activity and plant absorption mechanisms. Researchers have linked HS supplementation to augmented specific growth rates, higher feed efficiency and greater weight gain in aquaculture species. It has been observed that HS can boost the immune system of fish by increasing the activity of lysozyme and alkaline phosphatase in their mucus, as well as improving their ability to fight off harmful substances by raising oxyradical scavenging and glutathione levels. Moreover, HS has been associated with enhanced disease resistance, particularly against pathogens like *Vibrio* *harveyi*. From an environmental perspective, the utilization of HS promotes sustainability by diminishing dependence on synthetic fertilizers and antibiotics while facilitating the valorization of organic waste streams. HS could be environmentally friendly water additives that improve the efficacy and resilience of recirculating aquaculture systems, allowing sustainable aquaculture approaches.

Keywords: Natural water additives, sustainable aquaculture, water quality.

Introduction

Humic substances (HS) come from the breakdown of organic materials and are divided into three types based on how well they dissolve: humus (which doesn't dissolve), humic acids (which don't dissolve in acidic conditions) and fulvic acids (which dissolve in all conditions). HS originates from the organic matter of animals, plants and microbial detritus via microbial action. These chemicals are prevalent in both natural and artificial contexts [1, 2]. Understanding the properties and functions of HS is essential for harnessing their full potential in various fields. Further research is needed to explore the diverse applications of HS and optimize their use for sustainable aquaculture development.

The dissociation of these functional groups results in the formation of both polar and non-polar ends, which correspond to the hydrophilic and hydrophobic sections, respectively [3]. Both ends contribute to the mechanisms that confer beneficial HA activities. [4] HS are diverse natural substances lacking a definitive chemical composition. Functional groups such as carboxyl (-COOH), phenolic hydroxyl (-OH) and quinone enhance the stability and amphiphilicity of these compounds [5]. After the OH and COOH groups break apart, the polar end of the negatively charged part forms complexes with positively charged metals.

HS has been gaining research as feed supplements for terrestrial and aquatic animals. Improving fish feed with HS improved growth performance and immune response while reducing the incidence of skin lesions and the severity of infections [6–8]. Nonetheless, there exists an alternative application pathway for fish beyond feed: the aquatic environment, especially as a water additive in recirculating aquaculture systems. Enriching the water with HS mirrors the natural exposure, as up to 95% of the dissolved organic matter in aquatic ecosystems consists of humic substances [9, 10]. Another advantage of this exposure method is that pre-feeding larvae, which exhibit significantly high death rates [11, 12], can also be conditioned.

Application of Humic Substances in Recirculation Aquaculture Systems

Decomposed plant and animal waste, along with inorganic and organic pollutants, have an impact on water quality and aquatic life. Recent research informs this response on RAS humic substances' chemical, biological and environmental effects. Humic compounds' molecular structure changes with origin. RAS fulvic acids have both low and high oxygen molecules that are not fully saturated, similar to the fulvic acids found in the Suwannee River (SRFA) [13]. This variety in composition allows humic substances to complexate, adsorb and ion exchange with many contaminants, including heavy metals and organic molecules [13, 14].

RAS aquatic organisms benefit from humic substances. It can improve fish growth by increasing water quality and reducing stress. According to [15], applying humic acids to RAS can help aquatic plants like duckweed (*Lemna minor*) remove nutrients more efficiently, improving water quality and fish growth. Humic substances also promote microalgae development, which aquaculture uses as live feeds. That stimulate because they improve ionic nutrition availability and protect against abiotic stress [16].

HS significantly modulate fish immunological responses, enhancing their tolerance to environmental stressors. These substances enhance antioxidant defense systems and modulate the activity of biotransformation enzymes, which are essential in detoxification processes. Humic acids have been documented to enhance the activity of ethoxyresorufin-O-deethylase (EROD, an accepted biomarker for biotransformation enzymes, in Japanese medaka (*Oryzias latipes*) [17]. Moreover, humic substances have been linked to the decrease of stress-related enzymes, including aspartate aminotransferase (AST) and alanine aminotransferase (ALT), showing a capacity for alleviating physiological stress in fish [18]. The findings indicate that HS could function as advantageous additions in aquaculture by improving fish health and their ability to acclimate to environmental changes.

Hazardous for Aquatic Organisms

HS benefit aquatic organisms but can harm them under certain conditions. High concentrations of humic acid can cause stress in fish. It reduces complement components and coagulation factors in blood plasma to suppress the innate immune system [18]. Humic substances also affect algal photosynthetic activity, especially at higher concentrations [19]. Humic substances positively impact aquatic ecosystems, but their concentration must be monitored to prevent negative effects. Understanding their balance is crucial for healthy aquatic environments. To understand potential species impacts and manage levels, further research is necessary.

Impact of Humic Substances on Environment and Water Quality Management

HS is essential to RAS water quality. They reduce heavy metal and organic pollutant bioavailability and toxicity to aquatic organisms by binding. Humic acids reduce fish toxicity by complexing them with cupric ions [13]. Humic compounds also buffer pH and redox in aquatic environments. In RAS, water quality changes may negatively impact aquatic organisms, thus buffering capacity is essential [20]. Humic substances can improve aquatic conditions for fish health and growth, but further research is needed to understand their effects and regulate their concentrations in aquatic ecosystems, especially in RAS systems.

Effect on Nutrient Cycling

HS interact with nitrogen and phosphorus molecules to affect the RAS nutrient cycle. They help aquatic plants like duckweed remove ammonia nitrogen and total phosphorus, increasing water quality [15]. Humic substances also promote microalgae growth, which helps aquatic systems absorb nutrients and produce oxygen [16]. Humic substances play a crucial role in maintaining a balanced aquatic ecosystem by facilitating nutrient cycling, promoting plant growth and mitigating nutrient pollution. They help maintain water clarity, support diverse plant species and provide habitat for fish and other organisms in aquatic systems, such as freshwater lakes.

Potential Environmental Risks

While humic substances are generally beneficial, their accumulation in RAS can have unintended environmental consequences. For example, high levels of fulvic acids can lead to yellow discoloration of water, which may affect light penetration and photosynthesis in aquatic ecosystems [21]. Additionally, the use of humic substances as feed additives in aquaculture can lead to their accumulation in sediments, potentially altering the microbial community structure and nutrient cycling in aquatic systems [22, 23].

Use as Biostimulants

Aquaculture is increasingly using humic substances as biostimulants to boost the productivity and profitability of RAS. They can improve the growth performance of fish by enhancing nutrient uptake and reducing stress. For example, the addition of humic acids to fish feed has been shown to improve the specific growth rate (SGR) and feed conversion ratio (FCR) of fish culture such as Nile tilapia and Asian seabass [23]. Additionally, humic substances can stimulate the growth of microalgae, which are used as live feeds in aquaculture, by increasing their biomass concentration and pigment production [16].

Role in Water Remediation

RAS can also use humic substances for water remediation. They can bind to pollutants, such as heavy metals and organic compounds, reducing their concentrations in water. For example, humic acids can be complex with cupric ions, lowering their toxicity to aquatic organisms [13]. Additionally, humic substances can act as natural buffers, stabilizing pH and redox conditions in aquatic systems, which is particularly important in RAS where water quality can fluctuate significantly [24]. Previous research has demonstrated that humic compounds can improve the bioremediation capabilities of aquatic plants and microbes in RAS. Humic acid (HA) enhances aquatic duckweed's (*Lemna minor*) capacity to absorb TAN and TP from water, which in turn increases its nutrient removal effectiveness [15]. There will be a decreased need for external water treatment devices and more favorable conditions for aquatic creature growth as a result of this improvement in water quality. Critical water quality parameters, including dissolved oxygen, pH and nitrite/nitrate levels, can be stabilized by humic substances. For instance, studies have shown that humic acid can help fish grow better by lowering the amounts of free ammonia, nitrate and nitrite, while increasing orthophosphate levels in RAS. There a lower potential for changes in water quality and more stability in water chemistry when humic substances are present because they function as natural buffers. Furthermore [25] reported the study investigates the detoxification potential of various humic substances (HSs) on toxic nitrogen species in aquatic food organisms, revealing that HSs can reduce toxicity to varying degrees, with implications for improving recirculating aquaculture systems.

Enhancement of Fish Growth

There is evidence that humic substances can enhance the growth performance of RAS fish. For instance, according to [26], juvenile Asian seabass (*Lates calcarifer*) exhibited an increase in both the specific growth rate (SGR and weight gain when supplemented with fulvic acid in their diet. In a similar vein, humic acid has been demonstrated to improve feed utilization and growth rates in Nile tilapia (*Oreochromis niloticus*) when supplemented to water [15, 27].

Enhanced Efficiency in Feeding

Feed conversion ratios (FCR) can be improved with the use of humic compounds in RAS, leading to more efficient and cost-effective aquaculture operations. Better feed utilization by fish was shown by a significant reduction in feed conversion ratio (FCR) in a meta-analysis of studies on humic compounds as feed additives [23]. The capacity of humic compounds to facilitate nutrient absorption and metabolism in aquatic organisms is responsible for this increase in feed efficiency.

Health and Immunity Improvement

Immunostimulants like humic chemicals boost aquatic organisms' immune systems. Fulvic acid increases immune-related enzymes, including lysozyme and alkaline phosphatase, in rainbow trout (*Oncorhynchus mykiss*) skin mucous [2, 28]. This regulation of mucosal immunity can help aquaculture fish withstand illnesses and reduce antibiotic use. Furthermore, the study investigates the effects of humic substances on the microbiomes of juvenile European sea bass in a recirculating aquaculture system, revealing increased bacterial diversity, reduced potential pathogens and improved fish health parameters [22].

Antioxidant Values

Humic compounds contain antioxidants such as phenolic moieties that protect aquatic species from oxidative stress. For instance, rainbow trout gills with fulvic acid supplementation had higher TOSC and glutathione levels, boosting their antioxidant defenses [2, 29]. This reduction in oxidative stress can improve RAS fish health and stress tolerance.

Disease Resistance

RAS with humic substances improves aquatic organism disease resistance. Fulvic acid supplementation improves the survival rate of Asian seabass juveniles infected with *Vibrio harveyi*, a common aquaculture disease [30]. Humic chemicals boost immunity and lessen infection severity, increasing disease resistance. Humic substances can help aquaculture's circular economy by transforming waste into resources. Humate-containing wastes from humic preparation manufacture increase pond fish productivity and reduce synthetic fertilizer use [31, 32]. This method saves waste and improves sustainable aquaculture.

Recent research highlights the multifaceted applications of humate-based products in aquaculture, demonstrating significant benefits across environmental, biological and economic dimensions. Water quality improvement has been a key focus, with studies reporting enhanced nutrient removal efficiency facilitated by aquatic plants and microorganisms in humate-amended systems [27, 33]. In terms of fish health and performance, humates have been shown to promote growth by increasing specific growth rates and weight gain percentages [27, 30, 33]. Immune modulation is another important benefit, as evidenced by elevated lysozyme and alkaline phosphatase activities in fish mucus following humate application [2, 28]. Furthermore, humates exhibit antioxidant properties, such as increased total oxyradical scavenging capacity and glutathione levels, which contribute to overall fish health [2]. Their role in disease resistance has also been documented, with improved survival rates against pathogens like *Vibrio harveyi* [30]. From a sustainability perspective, the use of humates reduces dependence on synthetic fertilizers and antibiotics, supporting more environmentally friendly aquaculture practices [27, 33]. Additionally, humate-containing wastes can be repurposed into valuable inputs for aquaculture, offering promising avenues for waste management and circular resource use [34]. These findings collectively demonstrate the ability of humates to enhance aquaculture productivity while promoting ecological and economic sustainability.

Table 1: Key Applications and Findings of Humic Substances in RAS

Application	Key finding	Reference
Water quality improvement	Aquatic plants and microorganisms have increased their nutrient removal efficiency.	[15, 27, 33, 35]
Immune modulation	Fish mucus exhibits increased lysozyme and alkaline phosphatase activities.	[2, 30]
Growth promotion	The specific growth rate (SGR) and weight increase percentage of the fish have improved.	[15, 36, 37]
Antioxidant properties	An increase in total oxyradical scavenging capacity (TOSC) and glutathione concentrations was observed.	[28]
Disease resistant	The probability of survival against pathogens such as *Vibrio harveyi* has increased.	[22, 26]
Sustainability	Aquaculture decreased the need for synthetic fertilizers and antibiotics.	[35, 36]

Humic acids (HA) and fulvic acids (FA) can increase water quality, fish growth and immunological responses, which makes them useful in aquaculture. Recirculating aquaculture systems (RAS) utilize organic compounds to regulate water quality, disease resistance and sustainable production. This response discusses how humic chemicals improve aquatic creature development and health in RAS.

Conclusion

Humic substances are versatile compounds with significant potential in aquaculture recirculation systems. Their ability to interact with pollutants, stimulate biological processes and maintain water quality makes them valuable tools for improving the productivity and sustainability of RAS. However, their application requires careful consideration of their potential environmental risks and the need for further research into their molecular mechanisms of action. Humic substances can improve water quality, growth performance, immunological responses and sustainability in recirculating aquaculture systems. As natural bioremediation agents, growth promoters and immunological stimulants, they can help solve modern aquaculture problems. Humic compounds in RAS operations may enhance productivity, sustainability and environmental compatibility as the aquaculture industry expands.

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References

1. Kulikova NA. Interactions between Humic Substances and Microorganisms and. Molecules 2021; 26(2706):1–32.
2. Lieke T, Steinberg CEW, Pan B, Perminova IV, Meinelt T, Knopf K *et al*. Phenol-rich fulvic acid as a water additive enhances growth, reduces stress and stimulates the immune system of fish in aquaculture. Sci Rep 2021; 11(1):1–12.
3. Mirza MA, Ahmad N, Agarwal SP, Mahmood D, Anwer MK, Iqbal Z. Comparative evaluation of humic substances in oral drug delivery. Results Pharma Sci 2011; 1(1):16–26.
4. Jansen SA, Malaty M, Nwabara S, Johnson E, Ghabbour E, Davies G *et al*. Structural modeling in humic acids. Materials Science and Engineering C 1996; 4(3):175–9.

5. De Melo BAG, Motta FL, Santana MHA. Humic acids: Structural properties and multiple functionalities for novel technological developments. Materials Science and Engineering C 2015;

6. Gao Y, He J, He Z, Li Z, Zhao B, Mu Y *et al*. Effects of fulvic acid on growth performance and intestinal health of juvenile loach *Paramisgurnus dabryanus* (Sauvage). 2017.

7. Yamin G, Borisover M, Cohen E, van Rijn J. Accumulation of humic-like and proteinaceous dissolved organic matter in zero-discharge aquaculture systems as revealed by fluorescence EEM spectroscopy. Water Res 2017; 108:412–21.

8. Yilmaz S, Ergün S, Yıgıt M. Effects of dietary FARMARIN® XP supplement on immunological responses and disease resistance of rainbow trout (*Oncorhynchus mykiss*). Aquaculture 2018;496(July):211–20.

9. Haitzer M, Aiken GR, Ryan JN. Binding of mercury (II) to aquatic humic substances: Influence of pH and source of humic substances. Environ Sci Technol 2003; 37(11):2436-41.

10. Meinelt T, Kroupova H, Stüber A, Rennert B, Wienke A, Steinberg CEW. Can dissolved aquatic humic substances reduce the toxicity of ammonia and nitrite in recirculating aquaculture systems? Aquaculture 2010; 306(1–4):378–83.

11. Rojas-Tirado P, Pedersen PB, Vadstein O, Pedersen LF. Changes in microbial water quality in RAS following altered feed loading. Aquac Eng 2018; 81:80–8.

12. Fossmark RO, Vadstein O, Rosten TW, Bakke I, Košeto D, Bugten A V *et al*. Effects of reduced organic matter loading through membrane filtration on the microbial community dynamics in recirculating aquaculture systems (RAS) with Atlantic salmon parr (*Salmo salar*). Aquaculture 2020; 524(January):735268.

13. Wershaw RL. Application of a membrane model to the sorptive interactions of humic substances. Environ Health Perspect 1989; 83:191–203.

14. Perminova IV, Kulikova NA, IHSS. From Molecular Understanding to Innovative Applications of Humic Substances V1. 14th International Meeting of the International Humic Substances Society 2008; I.

15. Sarkheil M, Zahedi S, Safari O, Ahmadniaye motlagh H. Effects of humic acid on nutrient removal efficiency of aquatic duckweed (Lemna minor) and both growth performance and hemato-biochemical parameters of Nile tilapia (*Oreochromis niloticus*) cultured in water recirculating system. Int J Phytoremediation 2024; 26(4):481–92.

16. Popa DG, Lupu C, Constantinescu-Aruxandei D, Oancea F. Humic Substances as Microalgal Biostimulants—Implications for Microalgal Biotechnology. Mar Drugs 2022;20(5).

17. Yurchenko V, Morozov A. Responses of hepatic biotransformation and antioxidant enzymes in Japanese medaka (*Oryzias latipes*) exposed to humic acid. Fish Physiol Biochem 2022; 48(1):1–13.

18. Yurchenko VV, Morozov AA, Kiriukhin BA. Proteomics Analysis in Japanese Medaka *Oryzias latipes* Exposed to Humic Acid Revealed Suppression of Innate Immunity and Coagulation Proteins. Biology (Basel) 2022; 11(5).

19. Bährs H, Steinberg CEW. Impact of two different humic substances on selected coccal green algae and cyanobacteria-changes in growth and photosynthetic performance. Environmental Science and Pollution Research 2012; 19(2):335–46.

20. Ali M, Mindari W, Poernomo E. the Dynamics of pH, Ec and Redox of Pond Soil After Application of Humic Acid. Int J Adv Res (Indore) 2017;5(10):187–92.

21. Aguilar-Alarcón P, Gonzalez SV, Asimakopoulos AG, Mikkelsen Ø. Deciphering the Composition of Fulvic Acids from Recirculating Aquaculture Systems by Quadrupole Time-of-Flight Mass Spectrometry. Water (Switzerland) 2022; 14(16).

22. Louvado A, Cleary DFR, Pereira LF, Coelho FJRC, Pousão-Ferreira P, Ozório ROA *et al*. Humic substances modulate fish bacterial communities in a marine recirculating aquaculture system. Aquaculture 2021;544.

23. Rasidi R, Ardi I, Puspaningsih D, Prakoso VA, Jusadi D, Jayanegara A. Utilisation of Humic Substances as a Feed Additive in Aquaculture: A Meta-Analysis. Asian Fish Sci 2023; 36(4):182–91.

24. Datta A, Sanyal SK, Saha S. A study on natural and synthetic humic acids and their complexing ability towards cadmium. Plant Soil 2001; 235(1):115–25.

25. Meinelt T, Kroupova H, Stüber A, Rennert B, Wienke A, Steinberg CEW. Can dissolved aquatic humic substances reduce the toxicity of ammonia and nitrite in recirculating aquaculture systems? Aquaculture 2010; 306(1–4):378–83.

26. Zoheiri F, Hoseinifar SH, Mozanzadeh MT, Ahangarzadeh M, Lieke T, Van Doan H. Dietary fulvic acid increased growth, stress tolerance and disease resistance against Vibrio harveyi in Asian seabass (*Lates calcarifer*) juvenile. Aquac Rep 2023;32(August):101738.

27. Battah M, Dawah A, Ammar A, Salama M. Plankton Community, Water Quality and Growth Performance of Nile Tilapia As Affected By Humic Acid in Aquaculture Ponds. Egyptian Journal of Phycology 2013; 14(1):15–35.

28. Lieke T. Fulvic acid as water additive in aquaculture – A new way to deliver an immunostimulant to juvenile fish and fish larvae.

29. Abdollahzadeh Y, Mazandarani M, Hoseinifar SH, Lieke T, Van Doan H, Pourmozaffar S. Dietary fulvic acid improves immune, digestive and antioxidant parameters in juvenile white-leg shrimp (*Litopenaeus vannamei*) in a super-intensive system. Comp Biochem Physiol B Biochem Mol Biol 2025; 275:111011.

30. Zoheiri F, Hoseinifar SH, Mozanzadeh MT, Ahangarzadeh M, Lieke T, Van Doan H. Dietary fulvic acid increased growth, stress tolerance and disease resistance against Vibrio harveyi in Asian seabass (*Lates calcarifer*) juvenile. Aquac Rep 2023;32:101738.

31. Nosir W, Abdelkader M, Abdelkader MA. Effect of natural Additives on *Nigella sativa* Growth in Hydroponic System. The future Journal of Biology 2017; 2(4):11–30.

32. Das S, Mirjan S, Dey S, Mandal A, Patra A, Chowdhury D *et al*. Humifloc^{TM}: An improved solid waste responsible for sustainable aquaculture. J Clean Prod 2023; 430:139459.

33. Sarkheil M, Zahedi S, Safari O, Ahmadniaye Motlagh H. Application of humic acid in a water recirculating system: influences on total ammonia nitrogen (TAN) removal efficiency of biofilter and growth performance of Nile tilapia (*Oreochromis niloticus*). Aquaculture International 2024; 32(6):8079–94.

34. Jindo K, Olivares FL, Malcher DJ da P, Sánchez-Monedero MA,

Kempenaar C, Canellas LP. From Lab to Field: Role of Humic Substances Under Open-Field and Greenhouse Conditions as Biostimulant and Biocontrol Agent. Front Plant Sci 2020;11:1–10.

35. Ondrasek G, Rengel Z, Romic D. Humic acids decrease uptake and distribution of trace metals, but not the growth of radish exposed to cadmium toxicity. Ecotoxicol Environ Saf 2018;151:55–61.

36. Jusadi D, Aprilia T, Setiawati M, Agus Suprayudi M, Ekasari J. Dietary supplementation of fulvic acid for growth improvement and prevention of heavy metal accumulation in Nile tilapia fed with green mussel. Egypt J Aquat Res 2020; 46(3):295–301.

37. Rasidi R, Jusadi D, Setiawati M, Yuhana M, Zairin M, Sugama K. Dietary Supplementation of humic acid in the Feed of juvenile asian seabass, *Lates calcarifer* to counteract possible negative effects of Cadmium Accumulation on Growth and Fish Well-being when Green Mussel (*Perna viridis*) is used as a Feed ingredient. Aquac Res 2021; 52(6):2550–68.

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CHAPTER

Fish Health and Disease Control in Recirculating Aquaculture System

Yani Aryati
Center Research of Applied microbiology, National Research and Innovation Agency, Cibinong Science Center - Gedung Biologi, Cibinong, Nanggewer Mekar, Bogor, West Java, 1692, Indonesia

Isti Koesharyani
Research Center for Freshwater Aquaculture, National Research and Innovation Agency, Cibinong Science Center - Gedung Biologi, Cibinong, Nanggewer Mekar, Bogor, West Java, 1692, Indonesia

Muhamad Yamin*
Research Center for Freshwater Aquaculture, National Research and Innovation Agency, Cibinong Science Center - Gedung Biologi, Cibinong, Nanggewer Mekar, Bogor, West Java, 1692, Indonesia

Yuli Siti Fatma
Center Research of Applied microbiology, National Research and Innovation Agency, Cibinong Science Center - Gedung Biologi, Cibinong, Nanggewer Mekar, Bogor, West Java, 1692, Indonesia

Nur Syafira Khoirunnisa
Center Research of Applied microbiology, National Research and Innovation Agency, Cibinong Science Center - Gedung Biologi, Cibinong, Nanggewer Mekar, Bogor, West Java, 1692, Indonesia

Early Septiningsih
Research Center for Conservation of Marine and Inland Water Resources, National Research and Innovation Agency, Cibinong Science Center - Gedung Biologi, Cibinong, Nanggewer Mekar, Bogor, West Java, 1692, Indonesia

Corresponding Author: muha321@brin.go.id

Abstract

A sustainable fish farming method that provides a way to satisfy the increasing demand for fish worldwide is Recirculating Aquaculture Systems (RAS). The water consumption of these closed systems, which reuse and circulate water, can be as much as 99% lower than that of conventional aquaculture techniques. Additionally, RAS lessens the chance of fish escapes, disease transmission from wild populations and water contamination from bodies of water. However, the environmental conditions in a closed RAS system can increase fish stress and suppress the immune system, resulting in elevated susceptibility to pathogens such as bacteria, parasites, fungi and viruses. Understanding where these pathogens originate, how they infect fish and how to reduce their prevalence is critical for effective disease management. Chemical treatments play an important role in controlling or eliminating infections, but their application must be guided by a thorough understanding of pathogen biology and system dynamics. One of the important aspects of RAS is disease or pathogen prevention through the application of biosecurity to prevent the entry of pathogens into the system. The most common approach involves through screening and testing of fish during quarantine or isolation prior to being transferred into the main rearing system.

Keywords: disease, biosecurity, pathogen, RAS.

Introduction

Aquaculture is currently the fastest-growing food-producing industry worldwide and has been recognized as one of the key industries supplying millions of people with food and nutrition security, income and employment opportunities [1]. As a result, aquaculture has been linked to some difficulties such parasites and fish diseases [2]. For instance, it has been calculated that fish mortality costs Brazil a total of US$ 84 million per year [3].

The problem is very serious in poorer countries, so we need to quickly start preventing and controlling diseases. Fish get sick when three things happen together: a bad environment, a strong germ and a fish that can easily get sick. We group these diseases by what causes them: bacteria, viruses, fungi or parasites. Technologies for fish health management and biosecurity are already in place in aquaculture, but adoption of these technologies and optimal management practices is hampered by a lack of technical expertise [4].

To raise fish in recirculating aquaculture systems (RAS), the most important thing is managing their health. This includes having a good system in place and knowing a lot about fish health. Recirculating aquaculture systems (RAS) are intensive, self-contained aquaculture systems that reuse a significant amount of water. These systems lower the amount of water needed for fish farming by filtering and cleaning the water from the fish tanks before it is used again [5]. RAS raises fish in indoor tanks in a controlled environment as opposed to the conventional practice of raising fish outdoors in open ponds and raceways [6]. Over the past ten years, aquaculture has seen a new investment in the RAS system. By watching the water quality and managing the water that comes in, RAS helps aquatic animals grow faster and stay healthy at all stages of life [7].

RAS technology enables the production of fish with a bigger harvest size and more lucrative outcomes [8]. Furthermore, to improve the RAS technology further and to increase one's knowledge about using biosecurity to manage health. The essential component is fish production as well as encouraging higher fish production, for example by stimulating fish growth with optimal hydrodynamics, optimal light to increase growth, with suitable flows and pipelines to prevent sedimentation and the possibility that gas will appear in fishponds as H_2S. RAS systems operate under strict protocols, minimizing the use of antibiotics and chemicals, which can harm aquatic ecosystems and human health. RAS can integrate aquaponics, where nitrogen waste from fish is used as input for vegetable production, increasing the overall sustainability and profitability of the system [9].

Recirculating aquaculture systems for fish production been in use for many years. There are several various interpretations of RAS, in general it refers to a water exchange system where 90% of the volume of the system is recycled, with less than 10% water exchange of the system's volume per unit time [10]. The formula usually used is:

- Recirculation Rate (%):

$$Recirculation\ Rate\ (\%) = \frac{Water\ Flow\ to\ Tank\ \left(\frac{m^3}{h}\right)}{New\ Water\ \left(\frac{m^3}{h}\right) + Water\ Flow\ to\ Tank\ \left(\frac{m^3}{h}\right)}\ x\ 100$$

Where:

Water Flow to Tank (m^3/h): The amount of water flowing into the tank per hour.

New Water (m^3/h): The amount of new water being added per hour.

- Water Exchange Rate per Day (%):

$$Water\ Exchange\ Rate\ per\ Day\ (\%) = \frac{Per - day\ Water\ Exchange\ (m^3/day)}{Total\ Water\ Volume\ in\ the\ System\ (m^3)}\ x\ 100$$

Where:

Per-day Water Exchange (m^3/day): The amount of water exchanged in the system per day.

The system's total water volume (m^3): The total volume of water in the system.

- Water Exchange Every Day per kg of Feed (L/kg feed):

$$Daily\ Water\ Exchange\ per\ kg\ of\ Feed = \frac{Per\ day\ Water\ Exchange\ (m^3/day)}{Per\ day\ Feed\ Supply\ (kg/day)}$$

Where:

Per day Water Exchange (m^3/day): The volume of water exchanged per day in the system.

Per day Feed Supply (kg/day): The amount of feed supplied per day.

Compared to big ponds or flow-through systems, recirculating systems may have more erratic water quality. Variations in water quality, such as brief rises in nitrite or ammonia, can cause serious harm or illness on their own. These changes in the environment frequently result in immune system suppression and increased vulnerability to pathogens, organisms that cause disease, includes viruses, fungi, bacteria, parasites and disease outbreaks.

Systems that circulate encourage the disease transmission and the proliferation of several pathogenic organisms. This tendency can be attributed to a variety of factors, such as slower water turnover, the accumulation of biofilms and sediment, which can lead to the development of pathogens, in tanks, sumps or filtration components (particularly mechanical and biological filters) and higher fish densities in comparison to other culture systems. Overall, RAS offer a more sustainable and efficient approach to aquaculture, addressing key challenges such as water conservation, environmental protection and disease management while promoting local production and job creation [5].

Pathogens may become concentrated over time, meaning they are present in large quantities. The majority of infections are thought to be opportunistic, only infecting fish with compromised immune systems. However, infections can also infect healthy fish with sickness if they proliferate enough. Furthermore, a system's constant water flow can quickly spread germs, particularly if it lacks proper disinfection procedures or elements like ozone or UV sterilization. In recirculating systems, bacteria, parasites, fungi and viruses can all concentrate.

Bacterial disease

Many tiny living things live in recirculating aquaculture systems. These include bacteria that change nitrogen compounds, such as nitrifying bacteria, denitrifying bacteria and bacteria that change nitrate into ammonia. Other bacteria include bacteria that oxidize ammonium anaerobically (Anammox), microorganisms that reduce sulfate, microorganisms that oxidize sulfur and microorganisms that produce methane [11]. *Aeromonas species*, *Vibrio*, *Mycobacterium*, *Streptococcus*, *Yersinia ruckeri* [12] and *Flavobacterium columnare* are among the bacteria that seem to proliferate in recirculating systems (causes columnaris).

Several types of bacteria in the *Flavobacterium* group are extremely important opportunistic fish pathogens that are considered ubiquitous in the aquatic environment and are associated with significant losses during outbreaks of clinical disease [13]. *F. columnare* is linked to columnaris illness. The cause of the illness can be seen on the gills, but it's more common to find it on the skin. Columnaris usually doesn't happen on its own; something must hurt the fish or its surroundings to cause the disease to show up. When this happens, many fish can die, sometimes more than 70%. In tests of water om two saltwater and seven freshwater RAS, disease-causing organisms like *Bacillus cereus*, *Shigella* spp., *Vibrio* spp., *Photobacterium damsela* and *A. hydrophila* were found [14].

This is about the tiny living things that cause MIB (2-methylisoborneol (1,2,7,7-tetramethyl-exo-bicyclo [2.2.1]-heptan-2-ol and Geosmin (trans-1,10-dimethyl-trans-9-decalol) to be produced in recirculation aquaculture systems (RAS) are *Streptomyces roseoflavus*, *S. thermocarboxydus*, *Streptomyces cyaneofuscatus*, *Nocardia cf. fluminea*, *Pseudanabaena* sp., *Microcoleus* sp., *Phormidium tenue*, *Sorangium Nannocystis* [15].

Using (bacteria) phage therapy could be another way to fight bacteria, instead of using antibiotics. It could also help solve the problem of antimicrobial resistance and support the One Health approach. Phages are viruses that only infect bacteria and do not hurt other microbes or eukaryotic cells around them. Phage therapy is not new. It has been used for almost 100 years to treat bacterial infections in people [16]. Recirculating water helps deliver phages because they are small enough to go through filters and other barriers. This means they can stay in the system for a long time and move freely with the water [17]. However, we need to study the roles and activities of microbes in RAS more to help them boost plant growth and fight plant diseases better [18]. The types of microbes present during different steps of filtering recycled water in the RAS system can change a lot depending on different things. How many aquatic animals are being raised, how dirty the water is from fish waste and leftover, the water's pH and the chemicals in the water (like the amounts of nitrates and nitrites) can all change the makeup of the bacterial community [19]. The water temperature in the RAS also has an impact on which microbes grow [20].

Viral disease

Most viral diseases happen because there are no antiviral treatments and young fish are very likely to get sick. It's hard to create good vaccines for young fish and we don't know enough about how to make virus vaccines [21]. Also, it's often hard to spot viral infections, they can't be cured, they're hard to get rid of and they can cause many deaths, which leads to big losses. Viral diseases spreading through global trade is a big danger to fish farming. Moving animals that look healthy but are infected, carrier animals that don't show symptoms and shipping among the risks include contaminated eggs that pose a threat to fish farming's future [22].

In a RAS, good biosecurity means doing things like using seeds that are free of specific diseases, using safe water from the ground and having closed buildings that only a few employees can enter and those employees must follow strict biosecurity rules. Well-run RAS systems can greatly reduce or stop the entry of fish pathogens that must live in a host to survive. Death from virus infections can depend on how old the fish are or what the water temperature is. Viruses spread either horizontally or vertically. Horizontal transmission happens through things like bodily fluids, semen, urine and feces or ovarian fluid that are released into the water. Vertical transmission, on the other hand, is when the virus in the parent (in the ovaries or testicles) is passed to their offspring.

Viruses that infect fish include Necrotic Necrosis Virus (NNV), Viral Hemorrhagic Septicemia (VHS), Spring Viremia of Carp (SVC), Spleen and

Kidney Infection Virus (ISKNV) and Koi Herpes Virus (KHV). On the other hand, opportunistic fish pathogens are those that can grow and keep food safe in the water and they are often related to disease. This only occurs when the fish and its surroundings allow the virus to thrive. You can prevent fish from being exposed to obligate pathogens in a limited, controlled environment with only one species. However, you must always think of opportunistic pathogens as possible threats to fish health. This is particularly important in RAS systems, where pathogens can increase to harmful levels because of how water is used. Therefore, this section will cover some key opportunistic fish pathogens that can cause major issues in RAS when conditions are not good.

Aquaculture industry around the world has grown quickly in recent years. This has led to more aquaculture viruses appearing and being discovered. Because some viruses have a very large effect on the aquaculture industry worldwide, we must take steps to prevent diseases from being introduced to fish that could catch them. We must also lower the levels of infection to acceptable levels in fish populations that are already infected. While land-based, restricted, controlled monoculture offers a chance for much better control than more open, conventional ways of raising fish, the new RAS environment and the fish production is intense in these systems create a situation where new pathogens and diseases could become problems for RAS operators in the future.

Biosecurity keeps diseases out of growing areas or buildings. This also means controlling diseases that are already in an area to keep them from spreading. The main worry in biosecurity is anything that can carry diseases, like infected animals or objects. To have good biosecurity in aquaculture, use biosecurity steps in every part of the aquaculture process. This includes ponds and groups that handle aquaculture products sent to and from other countries. Some actions for dealing with viral diseases include quarantine, vaccination, temperature, using recommended stocking densities, filtering and irradiating incoming water with ultraviolet (UV) light and using chemicals to control viruses [2].

Paracites disease

Parasites like *Trichodina*, *Ichthyophthirius multifiliis* (White Spot) Infections in Fish, *Cryptocaryon*, *Amyloodinium*, *Costia* and monogeneans tend to grow and spread easily in RAS [23]. Other examples of these parasites are *Gyrodactylus*, *Chilodonella*, *Epistylis*, *Trichophrya*, *Ichthyophthirius*, *Ichtyobodo* and amoebic gill infestation.

The ciliated protozoan *Cryptocaryon irritans* is a harmful parasite that affects many marine teleosts in tropical and subtropical areas. For example, *Cryptocaryon irritans* can cause infection in industry aquaculture. Aquaculture industry has additionally raised the danger of spreading diseases because of high-density farming in closed environments, especially in recirculating aquaculture systems (RAS). This problem can be solved with RAS, solar radiation (UV) and ozone (O_3), which are frequently used to disinfect in industry aquaculture [24]. Numerous physical and chemical methods have been used to control the *C. irritans* parasite in aquaculture industry, while changing culture containers, the recommended techniques are immersion in copper or formalin [25].

Ectoparasites cause the most serious disease outbreaks in *Asian seabass*, cobia and pompano during their larval and juvenile stages. These parasites feed on mucous, tissues and other bodily fluids. *Cryptocaryoniasis*, *Amyloodiniosis*, *Trichodiniosis, Microsporidiosi*s and other infections caused by monogeneans, digeneans, copepods and isopods are the most common ecoparasitic infections in fish raised on RAS. They damage the epithelial layer, which leads to skin lesions that bleed. Many parasites carry bacteria and viruses, which can cause various infections in fish.

Fungal diseases of fish

The fungi that cause saprolegniasis are Oomycetes of the Saprolegnia genus, which are found in freshwater settings and are present in the RAS [26]. Saprolegniasis causes big financial problems for aquaculture businesses worldwide, harming both cold and warmwater fish. Recently, saprolegniasis has become a problem again in salmon farming after malachite green was banned [27]. Now, it is thought that 10% of all young Atlantic salmon raised on farms die from this disease [28].

Another fungus in freshwater is Epizootic Ulcerative Syndrome (EUS) Along with the rhabdovirus and the *Aeromonas hydrophila*, *Aphanomyces invadans* is linked to the illness outbreak [29]. More than 30 kinds of freshwater fish, including goby, guorami, catfish and snakeheads. The condition causes fish to become lethargic, which can eventually turn into inactivity or comatoseness. When the disease reaches an advanced stage, the vertebral column, visceral organs and head and bone tissues are frequently visible. Complete tail erosion is also typical. *Branchiom anchiomycosis* (Gill Rot) is caused by *Branchiomyces* spp. Species affected are carps, goldfish and eels. Fungal hyphae in the gills have an impact on hos because they block blood flow. Lamellar fusions and lamellar epithelial cell necrosis and proliferation may be seen. The illness can strike without warning and frequently progresses quickly, with losses of up to 30–50% happening in 2-4 days.

Ichthyophoniasis (Ichthyosporidiosis) is the cause of the problem is *Ichthyophonus* sp. Cods, herrings, flounders, the trout and droupers are among the species impacted. While some afflicted fish may not exhibit any outward signs, the cross sign is an outward sign of the illness It differs depending on the species. Affected fish can exhibit erratic swimming patterns and abdominal enlargement. Numerous white nodules up to 2 mm in diameter enlarge the internal organs (liver, kidney and spleen). Some afflicted fish also have nodules in their muscular tissues.

Because RAS farms are new aquatic environments and raise a lot of fish in a small space, new diseases could become issues for RAS operators in the future. This is true even though land-based closed containment aquaculture can control biosecurity better than older, more open fish farming methods. So, when fish get sick in RAS systems, fish health experts should think about causes other than the usual suspects.

Pathogen management in RAS

Pathogens may collect higher in compared to single-pass devices, RAS biofilters due to a poor dilution rate and high organic loading [30] and illnesses can be feasible when biofilms separate and come into contact with agricultural microbes. Effective system management and regulation of opportunist expansion by so-called "neutral bacteria" are the main factors affecting the biosecurity of RAS. Most of the water volume in RAS is recycled in the tanks after passing through mechanical and biological filters. However, because the pathogens propagate throughout the system and the addition of chemicals and antibiotics disturbs the biofilters' microbiome, illness prevention and treatment in these systems are difficult [17].

The most often utilized techniques for continually disinfecting water in RAS are ozone and UV treatment, either separately or in combination. Disinfection does not distinguish between populations of helpful microorganisms and pathogens. To prevent the growth of opportunists in the system, caution should be used in the dosages administered and the disinfection site [31]. After analyzing various disinfection efficiencies and came to the conclusion that a strong disinfection destabilizes the microbial population, which has detrimental consequences on cod larvae. Some of the technologies used include:

- Ozonation
- Ultraviolet irradiation
- Biocontrol of pathogenic microbes in RAS
- Green-water technology
- Microbially matured water
- Probiotic application

When compared to other system components, RAS biofilters are a substantial source of microorganisms and as such, they need further investigation into the dynamics and interactions of microbes in relation to specific design and input management. Control of autotrophic and heterotrophic bacteria is essential for maintaining optimum water quality and the health of farmed creatures. Effective control of the organic load lowers the possibility of ammonia and nitrite buildup, stops solids from accumulating in the system and lessens the growth of opportunistic pathogens and microorganisms that produce off flavors.

Conclusion

Some disease-causing organisms (pathogens) may thrive more readily in recirculating systems. A thorough knowledge of the locations of various pathogens (bacteria, parasites, viruses and fungi) may be present in a system and the recirculating system manager must understand how they could infiltrate a system. This knowledge is essential for creating efficient management procedures and for designing sound systems.

References

1. FAO. The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome; 2020. Available from: https://doi.org/10.4060/ca9229en
2. Opiyo MA, Marijani E, Muendo P, Odede R, Leschen W, Charo-Karisa H. A review of aquaculture production and health management practices of farmed fish in Kenya. Int J Vet Sci Med [Internet] 2018;6(2):141–8. Available from: https://doi.org/10.1016/j.ijvsm.2018.07.001
3. Tavares-Dias M, Martins ML. An overall estimation of losses caused by diseases in the Brazilian fish farms. J Par Dis [Internet] 2017;41(4):913–918. Available from: https://doi.org/10.1007/s12639-017-0938-y
4. Obiero KO, Waidbacher H, Nyawanda BO, Munguti JM, Manyala JO,

Kaunda-Arara B. Predicting uptake of aquaculture technologies among smallholder fish farmers in Kenya. Aquac Int [Internet] 2019;27:1689–1707. Available from: https://doi.org/10.1007/s10499-019-00423-0

5. Lal J, Anand V, Suparna D, Shubham K, Verma DK. Re-Circulatory Aquaculture Systems: A Pathway to Sustainable Fish Farming. Arc Cur Res Int [Internet] 2024;24(5):799–810. Available from: https://doi.org/10.9734/acri/2024/v24i5756
6. Narsale SA, Prakash P, Mohale HP, Baraiya R, Sheikh S, Kirtikumar PB, et al. Precision aquaculture: A way forward for sustainable agriculture. J Exp Agric Int [Internet] 2024;46(5):83–97. Available from: https://journaljeai.com/index.php/JEAI/article/view/2360
7. Attramadal KJK, Salveseh I, Xue RY, Oie G, Storseth TR, Vadstein O, Olseh Y. Recirculation as a possible microbial control strategy in the production of marine larvae. Aquac Engineer [Internet] 2012;46:27–39. Available from: https://doi.org/10.1016/j.aquaeng.2011.10.003
8. Holan B, Good C, Powell MD. Health management in recirculating aquaculture systems (RAS). Aquac Health Man [Internet] 2020;:281–318. Available from: https://doi.org/10.1016/b978-0-12-813359-0.00009-9
9. Vasdravanidis M, Alvanou MV, Lattos A, Papadopoulos DK, Chatzigeorgiou I, Ravani M, et al. Aquaponics as a promising strategy to mitigate impacts of climate change on rainbow trout culture. Animals [Internet] 2022;12(19):2523. Available from: https://doi.org/10.3390/ani12192523
10. Timmons MB, Ebeling JM, Wheaton FW, Summerfelt ST, Vinci BJ. Recirculating aquaculture system. Ithaca, NY: Cayuga Aqua Ventures; 2021.
11. Brown MN, Briones A, Diana J, Raskin L. Ammonia-oxidizing archaea and nitrite-oxidizing nitrospiras in the biofilter of a shrimp recirculating aquaculture system. FEMS Microb Ecol [Internet] 2013;83:17–25. Available from: https://doi.org/10.1111/j.1574-6941.2012.01448.x
12. Ringo E, Olsen RE, Gifstand TO, Dalmo RA, Amlund H, Hemre GI, et al. Prebiotics in aquaculture. Aquac Nutr [Internet] 2010;16:117–136. Available from: https://doi.org/10.1111/j.1365-2095.2009.00731.x
13. Starliper CE, Schill WB. Flavobacterial diseases: columnaris disease, coldwater disease and bacterial gill disease. In: Woo PTK, Bruno DW,

editors. Fish diseases and disorders. 2nd ed. Vol. 3. Wallingford: CABI International; 2021. p. 606–631.

14. King RK, Flick GJ Jr, Pierson D, Smith SA, Boardman GD, Coale CW Jr. Identification of bacterial pathogens in biofilms of recirculating aquaculture systems. J Aquac Food Prod Tech [Internet] 2004;13(1):125–133. Available from: https://doi.org/10.1300/J030v13n01_11
15. Rurangwa E, Verdegem MCJ. Microorganisms in recirculating aquaculture systems and their management. Rev Aquac [Internet] 2015;5:1–14. Available from: https://doi.org/10.1111/raq.12057
16. Kortright KE, Chan BK, Ko JL, Turner PE. Phage therapy: A renewed approach to combat antibiotic-resistant bacteria. Cell Host Microbe [Internet] 2019;25:219–232. Available from: https://doi.org/10.1016/j.chom.2019.01.014
17. Almeida GMF, Mäkelä K, Laanto E, Pulkkinen J, Vielma J, Sundberg LR. The Fate of Bacteriophages in Recirculating Aquaculture Systems (RAS)—Towards Developing Phage Therapy for RAS. Antibiotics [Internet] 2019;8(4):192. Available from: https://doi.org/10.3390/antibiotics8040192
18. Khalil S, Panda P, Ghadamgahi F, Rosberg AK, Vetukuri RR. Comparison of two commercial recirculated aquacultural systems and their microbial potential in plant disease suppression. BMC Microbiol [Internet] 2021;21(25). Available from: https://doi.org/10.20944/preprints202101.0155.v2
19. Ginayatov NS, Zalyalov IN, Absatirov GG, et al. Comparative Evaluation of the Effectiveness of Water Treatment Methods in Closed Water Supply Systems. Trans N.E. Bauman Kazan State Acad Vet Med 2012;:43–46.
20. Sergaliev NK, Kakishev MG, Ginayatov NS, Nurzhanova FK andronov EE. Microbiome structure in a recirculating aquaculture system and its connection to infections in sturgeon fish. Vet World [Internet] 2021;16(3):661–668. Available from: https://doi.org/10.14202/vetworld.2021.661-668
21. Dhar K, Manna SK, Allnutt FCT. Viral vaccines for farmed finfish. Virus Dis [Internet] 2014;25(2):117. Available from: https://doi.org/10.1007/s13337-013-0186-4
22. Rodgers J, Mohan CV, Peeler EJ. The spread of pathogens through trade

in aquatic animals and their products. Rev Sci Tech [Internet] 2011;30(1). Available from: https://doi.org/10.20506/rst.30.1.2034

23. Yanong RPE. Fish health management considerations in recirculating aquaculture systems—part 2: pathogens. University of Florida; 2003.
24. Lu G, Jiang B, Li ZC, Li AX. Ultraviolet light and ozone controls Cryptocaryon irritans infection in factory aquaculture. Aquaculture [Internet] 2022;548(1). Available from: https://doi.org/10.1016/j.aquaculture.2021.737598
25. Li Y, Jiang WB, Mo ZI, Li AX, Dan XM. Cryptocaryon irritans (Brown, 1951) is a serious threat to aquaculture of marine fish. Rev Aquac [Internet] 2021;:1–19. Available from: https://doi.org/10.1111/raq.12594
26. Jiang RHY, de Bruijn I, Haas BJ, Belmonte R. Distinctive expansion of potential virulence genes in the genome of the oomycete fish pathogen Saprolegnia parasitica. PLoS Genet [Internet] 2013. Available from: https://doi.org/10.1371/journal.pgen.1003272
27. Torto-Alalibo T, Miaoying TM, Gajendran K, Waugh ME, Van West P, Kamoun S. Expressed sequence tags from oomycete fish pathogen Saprolegnia parasitica reveal putative virulence factors. BMC Microbiol [Internet] 2005;5(46). Available from: https://doi.org/10.1186/1471-2180-5-46
28. Bruno DW, Van West P, Beakes GW. Saprolegnia and other oomycetes. In: Woo PTK, Bruno DW, editors. Fish diseases and disorders. 2nd ed. Vol. 3. Wallingford: CABI International; 2012. p. 669–720.
29. Lio-Po GD. Studies on several virus isolates, bacteria and a fungus associated with epizootic ulcerative syndrome (EUS) of several fishes in the Philippines [dissertation]. Burnaby (BC): Simon Fraser University; 1998. p. 281.
30. Schrader KK, Rubio SA, Piedrahita RH, Rimando AM. Geosmin and 2-methylisoborneol cause off-flavors in cultured largemouth bass and white sturgeon reared in recirculating water systems. N Am J Aquac [Internet] 2005;67:177–180. Available from: https://doi.org/10.1577/A04-070
31. Blancheton JP, Attramadal KJK, Michaud L, Roque d'Orbcastel E, Vadstein O. Insight into bacterial population in aquaculture systems and its implication. Aquac Engineer [Internet] 2013;53:30–39. Available from: https://doi.org/10.1016/j.aquaeng.2012.11.009

7
CHAPTER

The Role of Microbiome in Fish Farming with RAS System

Hessy Novita
Research Center for Veterinary Sciences, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta Bogor Km. 46, Cibinong 16911, West Java, 15418, Indonesia

Dewi Puspaningsih*
Research Center for Freshwater Aquaculture, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta-Bogor Km.46, Cibinong 16911, West Java, 15418, Indonesia

Iman Rusmana
Department of Biology, Faculty of Mathematics and Natural Sciences, Bogor Agricultural University (IPB),

Wahyu Pamungkas, Rasidi, Eri Setiadi and Edy Barkat Kholidin
Research Center for Freshwater Aquaculture, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta-Bogor Km.46, Cibinong 16911, West Java, 15418, Indonesia

Coresponding Author: dewi049@brin.go.id

Abstract

Aquaculture has become a key contributor to global food security, supplying nearly half of the world's fish consumption. However, its rapid expansion has raised environmental concerns, necessitating the adoption of sustainable practices. Among modern innovations, Recirculating Aquaculture Systems (RAS) offer a land-based, water-efficient alternative to traditional aquaculture methods. RAS provides enhanced control over environmental parameters and significantly reduces waste and water use, making it a promising solution for sustainable fish farming. A central aspect of RAS functionality is its microbial ecosystem, which plays a critical role in nutrient cycling, water quality maintenance and fish health. This review examines the factors influencing microbiome dynamics in RAS, including water quality parameters, feed composition, system design and stocking densities. It also explores the composition of RAS microbiomes, emphasizing the roles of key bacterial phyla and the gut microbiota of fish in enhancing immune function and nutrient assimilation. A balanced microbiome supports better fish growth, disease resistance and environmental sustainability. Advances in microbial

management such as the use of next-generation probiotics, integration of microalgae and application of omics technologies are shaping the future of aquaculture by enabling precise, eco-friendly and health-optimized systems. This underscores the importance of microbiome optimization as a cornerstone for improving productivity and sustainability in modern aquaculture.

Keywords: Recirculating Aquaculture Systems (RAS), Sustainable aquaculture, Microbiome dynamics, Fish health and immunity, Microbial management innovations

Introduction

Aquaculture is the practice of cultivating aquatic organisms such as fish, crustaceans and mollusks in controlled environments to meet the growing demand for seafood and support food security [1]. Aquaculture has become a vital sector in global food security, providing nearly 50% of the world's fish supply and economic growth, particularly in low-income countries [2, 3]. however, this growth has raised environmental concerns, including pollution, habitat degradation and conflicts over coastal space [4]. Sustainable practices are essential to mitigate these impacts, with strategies such as Integrated Multi-Trophic Aquaculture (IMTA), efficient feed management and waste reduction being highlighted as effective solutions [5, 6]. The integration of modern technologies, community involvement and robust governance can enhance sustainability, ensuring that aquaculture not only meets current food demands but also preserves aquatic ecosystems for future generations [5, 7]. The are two main approaches in aquaculture: traditional aquaculture and modern systems like Recirculating Aquaculture Systems (RAS).

Traditional aquaculture typically involves small-scale, low-technology methods passed down through generations, such as pond and cage culture. In pond systems, fish are raised in artificial or natural ponds, relying on the natural productivity of the water and sometimes supplemented with fertilizers or feed [8]. Cage culture confines fish in mesh enclosures within lakes or rivers, allowing for natural water exchange but exposing fish to environmental fluctuations and disease risks from wild populations [1]. Traditional systems are often extensive or semi-intensive, characterized by low stocking densities, minimal input and lower productivity, but they are deeply rooted in local culture and require less capital investment [9]. However, these methods can have environmental drawbacks, such as untreated waste discharge and reliance on natural water bodies, which can limit production and sustainability.

In contrast, RAS represent a modern, intensive approach to fish farming. RAS are land-based systems that continuously filter and reuse water through mechanical and biological processes, allowing for high stocking densities and greater control over environmental conditions. These systems minimize water usage and environmental impact by treating waste and maintaining optimal water quality parameters, supporting year-round production and reducing the risk of disease transmission from wild population. While RAS require higher initial investment and technical expertise, they offer significantly higher productivity and sustainability compared to traditional methods [10, 11].

Factors Influencing Microbiome Dynamics in RAS

Microbial stability and function in RAS are influenced by a complex interplay of biological, operational and environmental factors that affect microbiome dynamics. Based on recent study, the following summarizes important factors:

Water quality

Temperature, dissolved oxygen (DO), pH and other water quality parameters are important determinants of microbial activity in RAS. Since ammonia-oxidizing bacteria (AOB) like Nitrosomonas and ammonia-oxidizing archaea (AOA) prefer a restricted pH range (7–8.5), pH variations have a direct impact on nitrification effectiveness. Mechanical aeration is required to regulate conditions because elevated CO_2 levels, which are prevalent in RAS owing to fish respiration, can lower pH and hinder oxygen intake in fish. Microbial metabolic rates are influenced by temperature; warmer waters speed up nitrogen cycle but run the danger of oxygen depletion. To maintain nitrifying bacteria and avoid hypoxia, which can upset microbial populations and fish health, DO levels must be above 5 mg/L.

Probiotics and Feed Composition

Feed mix changes the availability of nutrients, which affects microbial dynamics. High-protein diets promote heterotrophic denitrifiers (*Pseudomonas*) and autotrophic nitrifiers (*Nitrosomonas*, *Nitrospira*) by increasing nitrogenous waste. Although probiotic supplements are meant to improve fish health, their direct effects on biofilter microbiomes might be minimal. According to studies, probiotic strains such as Bacillus species have no discernible impact on biofilter populations, indicating that their effects are restricted to fish guts rather than affecting microbial structures across the system. However, by boosting carbon and nitrogen substrates, feed-driven organic loading indirectly modifies water microbiomes, favoring taxa such as Bacteroidetes and Proteobacteria.

System Design and Biofilter Efficiency

Specialized microbial communities are housed in unique microenvironments produced by RAS compartmentalization. Complete ammonia-to-nitrate oxidation is carried out by nitrifying guilds such AOA (*Thaumarchaeota*), AOB (*Nitrosomonas*) and comammox *Nitrospira*, which dominate biofilters, the foundation of nitrogen removal. Surface area, hydraulic retention time and oxygen availability all affect biofilter effectiveness; mature systems use microbial succession to achieve stable nitrification. Heterotrophic overgrowth, which can outcompete nitrifiers and cause system breakdowns, is a risk associated with poorly constructed systems.

Stocking Density and Stressors

Elevated stocking density changes the diversity and function of microorganisms by increasing organic input. Under high-density conditions, for instance, African catfish RAS exhibited decreased microbial richness and the predominance of opportunistic diseases such as *Mycobacterium* spp., which were associated with increased levels of phosphorus and nitrogen. Overcrowding and other stressors raise fish cortisol levels and make them more vulnerable to dysbiosis. On the other hand, medium-density systems show more biodiversity and effective nutrient cycling, while balanced stocking levels support microbial stability. The buildup of organic matter in new RAS systems increases the potential of eutrophication, emphasizing the necessity of staggered stocking to give microbial communities time to adjust.

Microbiome Composition in RAS

Recirculating Aquaculture Systems (RAS) are complex environments where the microbiome plays a crucial role in maintaining water quality and ensuring the health of aquatic organisms. The microbiome in RAS is influenced by various factors, including water quality parameters and system design. Geosmin, a compound causing off-flavors in fish, is produced by specific bacterial groups, notably Actinomycetales, whose presence correlates with phosphate, calcium levels and redox potential, while oxygen levels and conductivity negatively correlate with geosmin concentration [12]. The microbial community in RAS is diverse and varies significantly between systems, with core taxa such as Flavobacterium, Cetobacterium and nitrifying guilds being common across different facilities [13].

The biofilter in RAS, crucial for waste management, hosts a variety of microbes, including nitrifying bacteria that convert ammonia to nitrate and denitrifying bacteria that further process these compounds [14]. The dynamic nature of microbial communities is evident in both water columns and biofilms, with feed administration affecting bacterial abundance and community stability [15]. Understanding these microbial dynamics and their interactions with environmental factors is essential for optimizing RAS design and operation, potentially reducing costs and improving system efficiency [13, 15]. Microbial imbalances (dysbiosis) can lead to disease outbreaks and system failures [16]. Therefore, understanding and optimizing the microbiome is crucial for improving RAS sustainability, fish health and productivity. Additionally, the stability of microbial communities in RAS is crucial for fish welfare, as evidenced by the dynamic succession of biofilm communities and the presence of pathogenic bacteria, which can be managed through careful monitoring of physicochemical conditions [15, 17]. Overall, RAS not only enhances microbial profiles but also improves the quality and yield of aquaculture products, highlighting its advantages over traditional methods [18].

Proteobacteria, Bacteroidetes and Verrucomicrobia are the phyla that usually dominate the water microbiome in freshwater RAS tanks, while particular taxa differ depending on system parameters like temperature and operational stage. Raceways, rearing tanks and biofilters are examples of RAS compartments with different microbial communities that maintain unique microbiomes tailored to their respective functional tasks [19]. When compared to flow-through systems, mature systems of RAS microbiomes show more microbial diversity and stability over time, which is linked to better production outcomes like increased larval survival. Still, there are temporal dynamics that can lead to changes in the structure and function of microbial communities.

These dynamics are controlled by things like feed supply, organic matter accumulation and water treatment techniques [17]. Additionally, factors such as fish type, loading intensity and system design influence microbiome composition, highlighting the need for tailored management practices to optimize microbial health [13]. Studies on African catfish and Atlantic salmon further demonstrate that stocking density and developmental stages affect microbial diversity and pathogen presence, suggesting that understanding these dynamics is essential for enhancing fish welfare and production outcomes in RAS [20].

Fish intestinal microbial community includes both autochthonous species that adhere to the intestinal mucosa and allochthonous species that do not because they are unable to do so or are outcompeted [21-23]. In addition to exhibiting great adaptability to environmental changes, microbial communities can also reflect physiological or environmental history, where the order in which microbes enter a community plays a significant role in determining the composition of the microbiome even in the presence of identical conditions [24]. Gut bacteria also support the growth, stimulation and defense of the host immune system in addition to giving the hosts vitamins, extracellular fatty acids and exogenous nutrients.

The gut microbiomes of various fish species are rather comparable. Proteobacteria, Fusobacteria, Firmicutes, Bacteroidetes, Actinobacteria and Verrucomicrobia are the predominant bacterial groupings. There is proof that zebrafish and common carp (*Cyprinus carpio*, L.) have a core gut microbiota [25-28]. Specifically, freshwater fish gut microbiomes frequently contain the Fusobacterial species *Cetobacterium somerae*, which can manufacture and most likely supply the host with vitamin B12 [25, 26].

Balanced Microbiome's Advantages for RAS

The balanced microbiome in Recirculating Aquaculture Systems (RAS) is crucial for enhancing fish health, growth performance and environmental sustainability. A diverse microbial community not only aids in water purification but also suppresses harmful pathogens, thereby reducing disease incidence among fish. This balance is essential for optimizing aquaculture productivity and minimizing ecological impacts. A balanced microbiome can inhibit the growth of opportunistic pathogens like *Vibrio harveyi* and *Vibrio rotiferianus*, leading to lower disease rates [29]. Studies indicate that systems with a predominance of beneficial bacteria experience enhanced disease resistance compared to those dominated by pathogens [30]. Microbial diversity is linked to improved nutrient cycling, which enhances fish growth rates and feed conversion efficiency [31]. Effective microbial management in RAS can lead to better water quality, thus promoting healthier fish and reducing the need for water changes [13].

RAS systems, supported by a balanced microbiome, can significantly reduce waste output and resource use, contributing to more sustainable aquaculture practices [32]. The presence of beneficial microbial communities can mitigate the environmental footprint of aquaculture by improving waste management and nutrient recycling [31]. Conversely, while a balanced microbiome offers numerous advantages, dysbiosis can lead to increased susceptibility to diseases and reduced productivity, highlighting the need for ongoing research and management strategies to maintain microbial health in aquaculture systems [30].

In addition, an optimal microbiome contributes to improved growth performance and feed conversion ratio (FCR) of fish. A healthy microbial community aids in the decomposition of organic waste and nitrogen conversion, creating an environment that supports efficient and optimal fish growth. Research on commercial RAS systems shows that good microbiome management correlates with better growth of fish seeds and higher survival rates throughout multiple production cycles [29].

Other benefits of a balanced microbiome are water use efficiency and reduced environmental impact. A balanced microbiome in Recirculating Aquaculture Systems (RAS) significantly enhances water use efficiency and minimizes environmental impact, allowing for water recycling rates of 90-99% compared to traditional aquaculture methods [11]. This high level of water reuse not only conserves freshwater resources but also mitigates the release of organic waste and nutrients into surrounding ecosystems, thereby reducing the risk of eutrophication and pollution in natural water bodies [33, 34]. Furthermore, RAS technologies incorporate advanced filtration and disinfection processes that maintain optimal water quality, promoting sustainable fish farming practices while supporting the integration of aquaponics, which utilizes nutrient-rich wastewater for vegetable production [35]. Consequently, RAS exemplify an environmentally friendly aquaculture solution that aligns with the principles of sustainable agriculture and resource conservation [36].

Microbiome management in recirculating aquaculture systems (RAS) has demonstrated significant benefits for fish health and production efficiency, particularly in Atlantic salmon farming. Studies indicate that the stability and diversity of microbial communities in water and biofilms correlate positively with fish health outcomes, as evidenced by increased microbial richness in RAS compared to flow-through systems [37]. Effective management practices, such as fallowing periods and regular microbiome monitoring, help maintain favorable microbial communities, thereby preventing pathogen outbreaks [29]. Additionally, the dynamic nature of the gut microbiome during critical life stages, such as smoltification, highlights the importance of microbial composition in influencing fish growth and health [20]. Overall, a balanced microbiome in RAS not only enhances fish welfare but also contributes to environmental sustainability by optimizing resource use and minimizing waste [13]. The future of microbial management and innovations in microbiome optimization is poised for significant advancements through tailored probiotics, phage therapy and the integration of omics technologies. These innovations promise to enhance health outcomes and sustainability in various applications.

Advances in Microbial Management in RAS

Advances in microbial management within recirculating aquaculture systems (RAS) focus on optimizing microbial communities to enhance water quality and overall system performance. The critical roles of diverse microorganisms in processes such as ammonia oxidation and organic matter mineralization, while also addressing challenges like pathogen proliferation and off-flavour production [29]. Integrating microalgae into RAS has emerged as a promising strategy, as they can utilize nutrient-rich waste streams, improve oxygenation and sequester carbon dioxide, thereby reducing production costs and enhancing system sustainability [38]. Furthermore, metagenomic approaches are being employed to characterize microbial communities more accurately, revealing the presence of fungi, viruses and bacteriophages, which can inform management practices and potential antipathogenic treatments (Metagenomics and metabarcoding experimental choices and their impact on microbial community characterization in freshwater recirculating aquaculture systems [39]. Collectively, these advancements underscore the importance of microbial management in achieving efficient and sustainable aquaculture practices.

Next-generation probiotics (NGPs) are emerging as a promising therapeutic approach for chronic ailments by specifically modulating gut health and immune function. These probiotics, such as *Akkermansia muciniphila* and *Faecalibacterium prausnitzii*, are engineered to target specific health issues, offering advantages over traditional probiotics through enhanced stability and tailored delivery methods [40, 41]. NGPs can produce bioactive compounds that compete with pathogenic bacteria, thereby restoring microbiome balance and potentially addressing antibiotic resistance [41, 42]. Furthermore, the integration of omics technologies, such as metagenomics and metabolomics, facilitates a deeper understanding of microbial interactions and their metabolic products, paving the way for personalized medicine [43]. In sustainable aquaculture, optimizing the microbiome through NGPs can enhance fish health and productivity, contributing to environmental sustainability [40, 42]. Overall, NGPs represent a multifaceted approach to improving health outcomes and addressing chronic diseases.

Conclusion

Aquaculture is crucial for global food security, supplying nearly 50% of the world's fish. While traditional methods face environmental challenges, Recirculating Aquaculture Systems (RAS) offer a sustainable alternative through water reuse and controlled environments. The success of RAS hinges on managing its complex microbiome, which is influenced by water quality, feed, system design and stocking density. A balanced microbiome in RAS is essential, directly improving fish health and growth, increasing water use efficiency (90-99% water recycling) and significantly reducing environmental impact. Advances in microbial management, including next-generation probiotics and omics technologies, promise to further optimize RAS for even more efficient, healthy and sustainable aquaculture practices.

References

1. Hei Z. Nurturing aquatic life: Exploring the art and science of fish culture. Asian J. Agric. Food Res. 2024; 8(2):2023–2024. https://doi.org/10.35841/aajfr-8.2.202.
2. FAO (Food and Agriculture Organization of the United Nations). The State of World Fisheries and Aquaculture (SOFIA). Rome: FAO, 2022; Available from: https://openknowledge.fao.org/items/11a4abd8-4e09-4bef-9c12-900fb4605a02.
3. Olaniyan ZM. Sustainability in Aquaculture: A Note. Recent Adv. Biol. Med. 2024; 9(5):1–2. https://doi.org/10.18639/rabm.2023.9800037.
4. Arshad S, Arshad S, Afzal S, Tasleem F. Environmental Impact and Sustainable Practices in Aquaculture: A Comprehensive Review. Saudi J. Life Sci. 2024; 9(11). https://doi.org/10.36348/sjls.2024.v09i11.005.
5. Arshad S, Arshad S, Afzal S, Tasleem F. Environmental Impact and Sustainable Practices in Aquaculture: A Comprehensive Review. Saudi J. Life Sci. 2024;9(11). https://doi.org/10.36348/sjls.2024.v09i11.005.
6. Sang HM, Minh-Thu P. Analysing Consequences of Aquaculture in Coastal Water Bodies of Ba Ria–Vung Tau, Vietnam on Sustainable Development Goals for Environmental Management. Asian Res. J. Agric. 2024; 17(4):186–198. https://doi.org/10.9734/arja/2024/v17i4514.
7. Tiutiunnyk H. Aquaculture Innovation and Multifunctional Centers:

Enhancing Aquaculture Market Development. Grail Sci. 2023; 29(29):32–34. https://doi.org/10.36074/grail-of-science.07.07.2023.002.

8. Sahoo P, Payra P. Basic Comparison between Traditional Farming and Modern Farming in Aquaculture. In: Chapter 15, 2023.
9. Mbuthia JM, Rewe TO, Kahi AK. Evaluation of pig production practices, constraints and opportunities for improvement in smallholder production systems in Kenya. Trop. Anim. Health Prod. 2015;47(2):369–376. https://doi.org/10.1007/s11250-014-0730-2.
10. Potnis AN, Ghanekar KV, Sinnarkar AN. System design, sustainable production and water quality research for Recirculating Aquaculture System (RAS). Int. Res. J. Eng. Technol. 2022; pp. 0–22. https://www.irjet.netJ.
11. Lal R, Lal N, Lal S. Re-Circulatory Aquaculture Systems: A Pathway to Sustainable Fish Farming. Arch. Curr. Res. Int. 2024;24(5):799–810. https://doi.org/10.9734/acri/2024/v24i5756
12. Lukassen MB, Menanteau-Ledouble S, de Jonge N, Schram E, Nielsen JL. Impact of water quality parameters on geosmin levels and geosmin producers in European recirculating aquaculture systems. J. Appl. Microbiol. 2022; 132(3):2475–2487. https://doi.org/10.1111/jam.15358.
13. Bartelme RP, Smith MC, Sepulveda-Villet OJ, Newton RJ. Component Microenvironments and System Biogeography Structure Microorganism Distributions in Recirculating Aquaculture and Aquaponic Systems. mSphere 2019;4(4). https://doi.org/10.1128/msphere.00143-19.
14. Prastowo BW, Penataseputro T. Microbial Diversity of Biological Filters in Recirculating Aquaculture Systems for Sand Lobster (*Panulirus homarus*) Rearing. IOP Conf. Ser. Earth Environ. Sci. 2023;1273(1). https://doi.org/10.1088/1755-1315/1273/1/012064.
15. Schoina E, Doulgeraki AI, Miliou H, Nychas G-JE. Dynamics of Water and Biofilm Bacterial Community Composition in a Mediterranean Recirculation Aquaculture System. Aquac. J. 2022; 2(2):164–179. https://doi.org/10.3390/aquacj2020008.
16. Attramadal KJK, Truong TMH, Bakke I, Skjermo J, Olsen Y, Vadstein O. RAS and microbial maturation as tools for K-selection of microbial communities improve survival in cod larvae. Aquaculture 2014; 432:483–490. https://doi.org/10.1016/j.aquaculture.2014.05.052.

17. Sergaliev NK, Kakishev MG, Ginayatov NS, Nurzhanova FK andronov EE. Microbiome structure in a recirculating aquaculture system and its connection to infections in sturgeon fish. Vet. World 2021; 14(3):661–668. https://doi.org/10.14202/VETWORLD.2021.661-668.

18. Saengsuk N, Boonanuntanasarn S, Boonchuen P, Phonsiri K, Kingwascharapong P, Petsong K, Pongsetkul J. Microbiota differences of giant river prawn (*Macrobrachium rosenbergii*) cultured in a recirculating aquaculture system (RAS) – A prototype vertical farming and traditional pond cultured system and their impact on autolysis rate and textural characteristics. Aquaculture 2024; 588:740959.

19. Diwan AD, Harke SN, Gopalkrishna, Panche AN. Aquaculture industry prospective from gut microbiome of fish and shellfish: An overview. J. Anim. Physiol. Anim. Nutr. (Berl). 2022;106(2):441–469. https://doi.org/10.1111/jpn.13619.

20. Lorgen-Ritchie M, Clarkson M, Chalmers L, Taylor JF, Migaud H, Martin SAM. A Temporally Dynamic Gut Microbiome in Atlantic Salmon During Freshwater Recirculating Aquaculture System (RAS) Production and Post-seawater Transfer. Front. Mar. Sci. 2021;8:1–14. https://doi.org/10.3389/fmars.2021.711797.

21. Navarrete P, Espejo RT, Romero J. PCR-TTGE analysis of 16S rRNA from rainbow trout (Oncorhynchus mykiss) gut microbiota reveals host-specific communities of active bacteria. PLoS One 2012; 7(2):1–10. https://doi.org/10.1371/journal.pone.0031335.

22. Llewellyn MS, Boutin S, Hoseinifar SH, Derome N. Teleost microbiomes: The state of the art in their characterization, manipulation and importance in aquaculture and fisheries. Front. Microbiol. 2014; 5:1–1. https://doi.org/10.3389/fmicb.2014.00207.

23. Givens CE, Ransom B, Bano N, Hollibaugh JT. Comparison of the gut microbiomes of 12 bony fish and 3 shark species. Mar. Ecol. Prog. Ser. 2015; 518:209–223. https://doi.org/10.3354/meps11034.

24. Sprockett D, Fukami T, Relman DA. Role of priority effects in the early-life assembly of the gut microbiota. Nat. Rev. Gastroenterol. Hepatol. 2018; 15(4):197–205. https://doi.org/10.1038/nrgastro.2018.8.

25. Roeselers G, Mittge EK, Stephens WZ, Parichy DM, Cavanaugh CM, Guillemin K, Rawls JF. Evidence for a core gut microbiota in the

zebrafish. ISME J. 2011; 5(10):1595–1608. https://doi.org/10.1038/ismej.2011.38.

26. van Kessel MAHJ, Dutilh BE, Neveling K, Kwint MP, Veltman JA, Flik G, Jetten MSM, Op den Camp HJM. Branchial nitrogen cycle symbionts can remove ammonia in fish gills. Environ. Microbiol. Rep. 2016; 8(5):590–594. https://doi.org/10.1111/1758-2229.12407.

27. Ghanbari M, Kneifel W, Domig KJ. A new view of the fish gut microbiome: Advances from next-generation sequencing. Aquaculture 2015; 448:464–475. https://doi.org/10.1016/j.aquaculture.2015.06.033.

28. Tarnecki AM, Patterson WF, Arias CR. Microbiota of wild-caught Red Snapper (Lutjanus campechanus). BMC Microbiol. 2016; 16(1):1–10. https://doi.org/10.1186/s12866-016-0864-7.

29. Rurangwa E, Verdegem MCJ. Microorganisms in recirculating aquaculture systems and their management. Rev. Aquac. 2015; 7(2):117–130. https://doi.org/10.1111/raq.12057.

30. Infante-Villamil S, Huerlimann R, Jerry DR. Microbiome diversity and dysbiosis in aquaculture. Rev. Aquac. 2021; 13(2):1077–1096. https://doi.org/10.1111/raq.12513.

31. Lorgen-Ritchie M, Clarkson M, Chalmers L, Taylor JF, Migaud H, Martin SAM. Microbiomes in the context of developing sustainable intensified aquaculture. Front. Microbiol. 2023;14(June):1–16. https://doi.org/10.3389/fmicb.2023.1200997S.

32. Moschos K, Kormas KA, Karayanni H. Prokaryotic diversity in marine and freshwater recirculating aquaculture systems. Rev. Aquac. 2022;14(4):1861–1886. https://doi.org/10.1111/raq.12677.

33. Yusoff FM, Umi WAD, Ramli NM, Harun R. Water quality management in aquaculture. Cambridge Prism. Water 2024;2. https://doi.org/10.1017/wat.2024.6.

34. Owatari Shizuo M, Pedreira Mouriño JL. Practical and essential information on water reuse systems in experimental aquaculture production: a descriptive review. SDRP J. Aquac. Fish. Sci. 2020;3(1):186–202. https://doi.org/10.25177/jaffs.3.1.ra.10628.

35. Goddard S, Delghandi M. Importance of the Conservation and Management of Freshwater to Aquaculture. In: Elsevier Inc.; 2020. p. 1–5. https://doi.org/10.1016/B978-0-12-409548-9.11954-2.

36. Xue S, Kui L, Sharifi R, Chen J. Editorial: The role of microbiome in sustainable agriculture. Front. Microbiol. 2024;15. https://doi.org/10.3389/fmicb.2024.1388926.

37. Minich JJ, Poole AC, Sogin ML, Knight R, Sanders JG. Microbial ecology of Atlantic salmon (*Salmo salar*) hatcheries: Impacts of the built environment on fish mucosal microbiota. Appl. Environ. Microbiol. 2020; 86(12):1–19. https://doi.org/10.1128/AEM.00411-20.

38. Ende S, Henjes J, Spiller M, Elshobary M, Hanelt D, Abomohra A. Recent advances in recirculating aquaculture systems and role of microalgae to close system loop. Bioresour. Technol. 2024;407:131107. https://doi.org/10.1016/j.biortech.2024.131107.

39. Rieder J, Kapopoulou A, Bank C, Adrian-Kalchhauser I. Metagenomics and metabarcoding experimental choices and their impact on microbial community characterization in freshwater recirculating aquaculture systems. Environ. Microbiome 2023;18(1):1–21. https://doi.org/10.1186/s40793-023-00459-z.

40. Loo KY, Thong JYH, Tan LTH, Letchumanan V, Chan KG, Lee LH *et al*. A Current Overview of Next-Generation Probiotics and Their Prospects in Health and Disease Management. Prog. Microbes Mol. Biol. 2024;7(1):1–33. https://doi.org/10.36877/pmmb.a0000457.

41. Abouelela ME, Helmy YA. Next-Generation Probiotics as Novel Therapeutics for Improving Human Health: Current Trends and Future Perspectives. Microorganisms 2024; 12(3). https://doi.org/10.3390/microorganisms12030430.

42. Tiwari A, Krisnawati DI, Susilowati E, Mutalik C, Kuo TR. Next-Generation Probiotics and Chronic Diseases: A Review of Current Research and Future Directions. J. Agric. Food Chem. 2024. https://doi.org/10.1021/acs.jafc.4c08702.

43. Satokari R. Modulation of gut microbiota for health by current and next-generation probiotics. Nutrients 2019;11(8):11–14. https://doi.org/10.3390/nu11081921.

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CHAPTER

Neon Tetra Farming in Indonesia: A Sustainable Approach through Recirculating Aquaculture Systems (RAS)

Muhamad Yamin*
Research Center for Freshwater Aquaculture, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta-Bogor Km. 46, Cibinong 16911, West Java, 15418, Indonesia

Ruby V. Kusumah
Research Center for Freshwater Aquaculture, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta-Bogor Km. 46, Cibinong 16911, West Java, 15418, Indonesia

Agus Priyadi
Research Center for Conservation of Marine and Inland Water Resources, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta-Bogor Km. 46, Cibinong 16911, West Java, Indonesia

Yani Aryati
Research Center for Applied Microbiology, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta-Bogor Km. 46, Cibinong 16911, West Java, 15418, Indonesia

Rendy Ginanjar
Research Center for Conservation of Marine and Inland Water Resources, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta-Bogor Km. 46, Cibinong 16911, West Java, Indonesia

Alimuddin Paada
Agricultural Faculty, Alchairat University, Central Sulawesi, Indonesia

Corresponding Author: muha321@brin.go.id

Abstract

The major production centers of neon tetra (*Paracheirodon innesi* Myers, 1936) in Indonesia is in Bojongsari District, Depok City-west java province, which lies near to capital city of jakarta and constrained by limited land and water resources. This paper discusses production of neon tetra fish seed management and the application of a zero-water exchange recirculation system (ZWERS) in rearing neon tetra to increase stocking density. In the Bojongsari Subdistrict, most neon tetra production is undertaken by small-scale farmers organized in fish farming groups (POKDAKAN), encompassing activities such as broodstock production, seed enlargement and marketing. Fish rearing is carried out in glass tanks (100 cm long) with aerated stagnant water. The main water source for fish rearing comes from ground wells. Fish seeds are fed moina since they are 4 days old after hatching and after they are large enough, they are given mixed feed (moina, bloodworms, silkworms, commercial pellets). The age of broodstock is at least 4 months with a fish density of 200 - 400 ind/tank, feeding frequency three times a day, the broodstock produces a maximum of 6-7 months, the production schedule for each set of broodstock is once every two days, the initial feed is artemia. The application of a zero-water exchange recirculation system allows for a neon tetra stocking density up to three times higher compared to stagnant water systems, with minimal impact on survival rate, body length, total body weight and daily growth rate. This system is particularly beneficial in areas facing land and water constraints.

Keywords: *Paracheirodon innesi*; water recirculation system; production, stocking density.

Introduction

The neon tetra (*Paracheirodon innesi*) (Myers, 1936) is a significant species in the global ornamental fish industry, particularly in markets across the United States, Europe and Asia [1]. Neon tetras, together with Guppy (*Poecilia reticulata*), contribute over 14% and approximately 25% of the total trade volume, respectively [2]. Approximately 1.8 million neon tetras were imported into the United States, with a total value of US$175,000 [3]. By 1992, demand in the country had reached 22.7 million fish, with projections indicating continued growth [4]. Most neon tetras in the global market are supplied by fish farms in Southeast Asia, with only a small portion originating from wild populations [3].

Indonesia is one of the major producers of neon tetras [5]. The production center is in Bojongsari District, Depok, West Java, where farming has been established for decades [6, 7]. The industry encompasses broodstock management, spawning, larval rearing, juvenile cultivation, grow-out and commercial distribution [6]. However, rapid urbanization poses significant challenges to the sustainability and productivity of the neon tetra industry. Rising land prices and declining groundwater quality due to urban pollution hinder the expansion of aquaculture areas. Additionally, the increasing presence of pathogens further threatens production efficiency and long-term sustainability.

A total of 20.6 million neon tetras were produced in Depok in 2022 [8] (Figure 2) which are mostly produced by small-scale farmers organized into Fish Farmer Groups (POKDAKAN) [5]. These farmers often face constraints in capital, technical expertise and access to advanced technologies. As a result, most neon tetra production relies on stagnant water systems, which are highly susceptible to disease outbreaks that can lead to significant mortality. Due to its location near Indonesia's capital city, the development of the neon tetra industry in Depok is constrained by limited land availability and rapid urban expansion, including residential and industrial growth, which contributes to water quality degradation through urban pollution. [5, 7].

This paper reviews the biological and ecological aspects of neon tetra (*Paracheirodon innesi*) and explores the application of Recirculating Aquaculture Systems (RAS) in neon tetra farming as an innovative solution to support sustainable production, improve water quality management and enable higher stocking densities without compromising fish health or growth performance. Overall, the paper aims to provide a comprehensive understanding of the species' environmental requirements and aquaculture strategies to promote sustainable and economically viable neon tetra production.

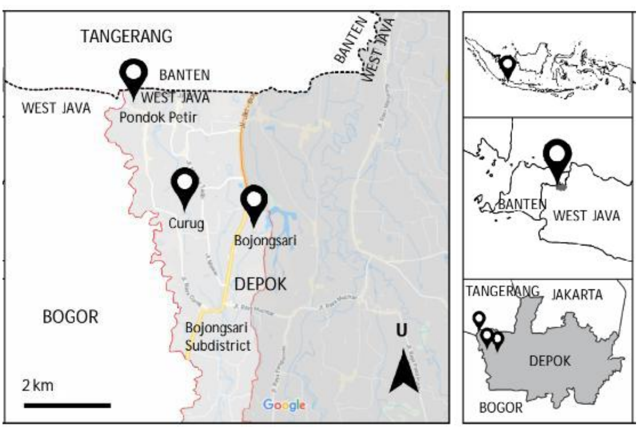

Fig. 2: The three main centers of neon tetra (Paracheirodon innesi) production in Bojongsari District, Depok, West Java: Pondok Petir, Curug and Bojongsari.

Neon Tetra Aquaculture and RAS System

Biology of Neon Tetra

Neon tetras, members of the family Characidae and order Characiformes, are native to the Amazon Basin in South America [9]. They inhabit blackwater and clearwater streams within the Ucayali-Solimões and Purus rivers [10]. Mature fish typically range from 2.2 to 3.0 cm in length, has adhesive and round-shaped eggs measure between 0.9 and 1.0 mm in diameter. Their eggs hatch within approximately 30 hours at water temperatures of 25–26.5°C. Recently, neon tetras have been successfully breeding and mass production in outside their native habitat [11].

Current Farming Practices on Neon Tetra in Depok, Indonesia

Small-scale fish farmers in Depok, West Java, Indonesia, have successfully established breeding and mass production of neon tetra in aquaculture (Figure 3) [12, 13]. Male and female broodstock (total length: 2.23 and 2.33 cm) are reared separately until they reach gonadal maturity. Once mature, a single pair is placed in a small breeding container (approximately 15 cm in length) with a water depth of 1–2 cm. After spawning, the broodstock are removed, allowing the eggs to develop and hatch. The larvae are then transferred to rearing tanks until they reach marketable size [11].

Most neon tetra production occurs indoors, utilizing 100 cm-long and 50 cm in width glass tanks with a maximum stocking density of 500 fish per tank which lies into 3 to 4 tiers to optimize the space. Farmers primarily employ a stagnant water system, replacing approximately 30% of the water daily [11].

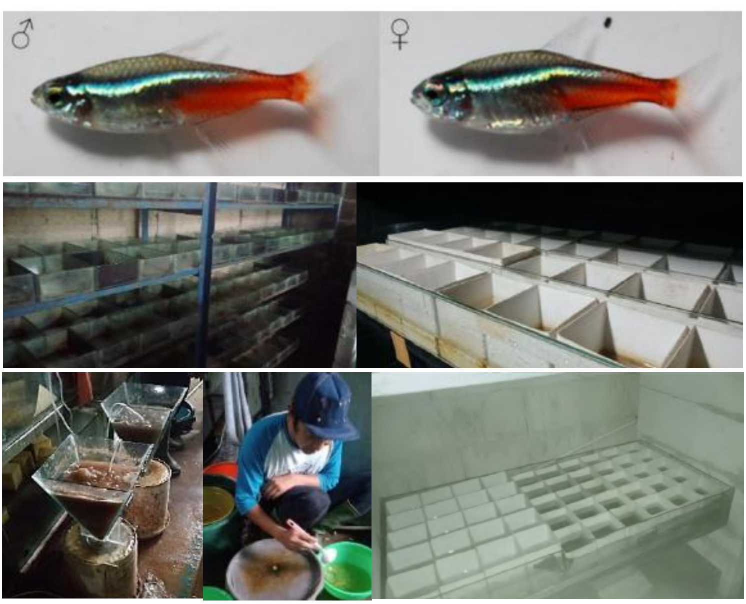

Fig. 3: Breeding activities of neon tetra at a small-scale farm in Depok, West Java.

The application of stagnant water systems in neon tetra farms frequently experiences disease outbreaks, occasionally leading to mass mortality. The primary diseases affecting neon tetras are caused by protozoan parasites from the genus Pleistophora (*Microsporidia*) and bacterial pathogens such as *Aeromonas* spp. and *Pseudomonas* spp [14]. Due to groundwater remaining the primary water supply for neon tetra farming in the region, limited availability of water and land constrains production expansion.

Aplication RAS on Neon Tetra production

Potensial RAS on neon tetra production

Optimizing stocking density is essential for maximizing neon tetra production. However, higher stocking densities intensify competition for resources such as feed and space, potentially impacting survival, growth, behavior, health and water quality [15, 16]. High stocking densities are known to induce stress, which can make fish more susceptible to diseases [17]. This often results in reduced growth rates, excessive waste accumulation, disease outbreaks and decreased survival rates.

In neon tetra farms, fish are predominantly reared using stagnant water systems, with a maximum stocking density of approximately 500 individuals per tank [11]. According to the farmers, increasing densities beyond this level typically results in stunted growth and heightened disease susceptibility. The implementation of RAS enables higher stocking densities without significantly compromising fish health or growth.

A pilot-scale study conducted at a neon tetra farming in Depok (Figure 4) showed that RAS effectively supports stocking densities two to three times higher than stagnant systems up to 1,500 individuals per tank without adversely affecting growth or survival. Neon tetras reared in recirculating systems exhibited high survival rates (>92%) across densities ranging from 500 to 1500 individuals per 100 cm-long tank. The fish maintained normal body length and weight, with no significant differences observed among the different stocking densities. The ability of RAS to maintain fish health at elevated stocking densities can be attributed to its ability to stabilize key water quality parameters, including pH, dissolved oxygen (DO) and temperature. Additionally, total dissolved solids (TDS) levels in RAS were lower and more stable than those in stagnant systems, which tend to experience frequent fluctuations and higher TDS levels (Table 2). These findings emphasize the potential of RAS to maintain optimal water quality while supporting higher stocking densities [18]. Several studies have demonstrated that RAS can support high survival rates across various fish species even at increased stocking densities [19–23]. In contrast, stagnant systems frequently suffer from deteriorating water quality, which often results in disease outbreaks [14]. These findings suggest that integrating RAS into neon tetra farming could significantly improve production efficiency by enabling higher stocking densities within existing infrastructure.

A

B.

Fig. 4: Overview of water management systems used in neon tetra farming in Bojongsari District, Depok, West Java. A. stagnant water system; B. Recirculating Aquaculture Systems (RAS).

Water Quality in a Water Recirculating System

Water quality parameters such as temperature, pH, dissolved oxygen (DO) and total dissolved solids (TDS) play a vital role in fish metabolism, growth and overall physiological function, particularly in captive environments [24, 25]. Fish require stable and optimal conditions for normal development, while extreme fluctuations can induce stress and hinder growth [24].

A pilot study implementing RAS in neon tetra farming revealed that temperature, pH, DO and TDS levels remained within the optimal range for fish rearing, with fewer fluctuations compared to stagnant systems. An overview of water quality parameters for neon tetra culture in RAS and stagnant systems in Depok is summarized in Table 2. Water temperatures were maintained between 27–29°C, closely resembling the species' natural habitat [26]. Although slightly above the optimal breeding range, the fish exhibited normal behavior and growth patterns [27–29]. Over time, conductivity, pH and TDS increased due to organic waste accumulation, illustrating the dynamic nature of recirculating systems [30]. Maintaining DO levels above 6 mg/L is essential for fish well-being and is achieved through continuous aeration and water recirculation [31, 32]. DO concentrations below 5–6 mg/L can induce hypoxia, causing stress, growth inhibition, increased disease susceptibility and mortality [33]. Severe oxygen depletion (<1 mg/L) can lead to large-scale fish mortality in aquatic environments [34].

Recirculating water facilitates the transfer of particulate matter from the rearing tanks to the filtration unit, preventing the accumulation of harmful substances such as ammonia, nitrite and nitrate [31, 35–37]. Accumulated particulates in rearing tanks can adhere to fish gills, causing irritation and reducing oxygen uptake [32, 36, 38]. Additionally, the ammonification of organic waste produces toxic ammonia, while decaying particulates contribute to oxygen depletion through microbial respiration [32]. Ammonia in its unionized form (NH_3) is highly toxic to fish and can cause sub-lethal effects, such as reduced growth or lethal outcomes at high concentrations [36]. Moreover, elevated nitrite levels in the bloodstream can bind to hemoglobin, forming methemoglobin, which is not effective for oxygen transport. This results in hypoxia, further impairing fish behavior, physiology, reproductive performance and potentially reducing population size by up to 20% [37].

Table 2: Water quality parameters in the rearing tanks of recirculating aquaculture systems (RAS) and stagnant water systems for neon tetra.

Parameters	Units	RAS System	Stagnant System	References
Temperature	°C	27.40–28.48	25–27	5–33
pH	—	5.59–8.09	4–6	4.39–7.3
Dissolved Oxygen (DO)	Mg/L	5.22–6.07	4–6	0.32–3.29
Total Dissolved Solids (TDS)	Mg/L	276–386	1.2–1.4	—

Bacteria

Bacteria play a crucial role in maintaining water quality and supporting the health of aquatic organisms by facilitating nitrification and suppressing pathogenic microorganisms. Nitrifying bacteria, such as *Nitrosomonas* and *Nitrobacter*, convert toxic ammonia into nitrite and subsequently into the less harmful nitrate, thereby preventing the accumulation of nitrogenous waste [31, [36, 37]. In addition, probiotic bacteria like *Lactobacillus* and *Bacillus* inhibit the growth of pathogenic bacteria, including *Aeromonas* and *Vibrio*, through competitive exclusion and the production of antimicrobial compounds [32]. However, poor water quality—characterized by elevated organic matter, increased ammonia levels and reduced dissolved oxygen can promote the proliferation of harmful bacteria such as *Vibrio, Aeromonas* and *Pseudomonas*, leading to diseases like septicemia and ulcerative infections [38]. Microbial imbalances caused by a decline in beneficial bacteria can further increase the prevalence of pathogens, reduce fish survival rates and negatively impacting aquaculture productivity [37].

A pilot study implementing a RAS in neon tetra farming revealed differences in bacterial communities between the rearing and biofilter tanks. Although potentially pathogenic bacteria such as *Vibrio* spp. and *Aeromonas* spp. were detected in the biofilter tank water, their concentrations were relatively low (1.06×10^4 to 2.6×10^4 CFU m/L) and did not negatively affect the neon tetras. Facultative anaerobes like *Aeromonas sobria* and *A. hydrophila* possess virulence factors activated through quorum sensing, which can potentially cause infections in neon tetras [39]. However, their low abundance may be attributed to the application of UV treatment before water enters the rearing tank, as well as the aerobic conditions in the rearing environment, which likely suppressed their growth.

On the other hand, beneficial bacteria such as *Bacillus* spp. and *Micrococcus* spp. were identified in water samples from both the rearing and biofilter tanks [40]. These bacteria are known to inhibit pathogens, improve water quality, enhance nutrient absorption and support overall fish health in aquaculture [41–43]. The UV treatment at 254 nm appeared effective in controlling bacterial populations by damaging their DNA and proteins, thereby limiting their proliferation [44, 45].

Implementation and Challenges of RAS in Small-Scale Neon Tetra Farming

Recirculating Aquaculture Systems (RAS) have been tested in small-scale neon tetra farms to enhance water quality management and support higher stocking densities. Unlike conventional stagnant water systems that require frequent water exchanges, RAS maintains a stable aquatic environment through continuous filtration and aeration. This approach is particularly advantageous for urban aquaculture settings such as Depok, Indonesia where land and water resources are limited.

The basic structure of RAS consists of rearing tanks linked to biofilters, aeration systems and circulation pumps. The biofilter plays a key role in converting toxic ammonia into less harmful nitrates via nitrification, while aeration systems ensure optimal dissolved oxygen levels for fish health. By stabilizing water parameters and minimizing disease risks, RAS enables farmers to increase stocking densities beyond traditional thresholds, thereby enhancing production efficiency. Moreover, RAS reduces water consumption and labor requirements by minimizing the need for daily siphoning and water replacement, positioning them as a sustainable solution for neon tetra farming.

Despite their advantages, several challenges hinder the widespread adoption of RAS among small-scale neon tetra farmers. Successful implementation requires technical knowledge, routine system maintenance and a willingness to shift from conventional practices. High initial costs associated with infrastructure, electrical upgrades and equipment acquisition combined with elevated energy consumption are key barriers for farmers [46].

Due to the small size of neon tetras, farming in Depok is predominantly conducted indoors using 1-meter-long glass tanks equipped with aeration systems. These tanks are considered efficient for mass production, as they simplify daily operations such as monitoring, siphoning and harvesting. Some farmers have made initial attempts to implement basic water recirculation systems. However, due to limited technical expertise, these systems often perform inefficiently. Common problems include undersized biofilters and improper placement of UV sterilizers for example, installing UV lamps within the filter chamber (Figure 5).

A pilot study on RAS implementation in Depok showed that establishing a functional system requires additional equipment such as submersible pumps, UV lamps, bio-balls, coral fragments, dacron filter media and circulation piping. Notably, an increased electrical load may be required, as many farmers share electricity with their homes and the additional equipment often exceeds the available supply. Space limitations were another challenge, as most facilities were fully occupied by rearing tanks, leaving minimal room for extra biofilters unless tanks were removed or repurposed.

Nevertheless, these limitations were offset by significant improvements in productivity. RAS allowes stocking densities to increase from 500 to 1,500 individuals per tank. Additionally, operational efficiency improved through reduced labor demands for siphoning and water exchange. Given that much of the necessary infrastructure is already in place, transitioning to a RAS setup primarily involves the addition of biofilters and circulation components making the upgrade both practical and feasible for small-scale farmers.

Recommendations and Future Perspectives

To facilitate the successful adoption of RAS in small-scale neon tetra production, several strategies can be implemented. Financial support through government initiatives, cooperative funding and microfinance programs can help alleviate the burden of high initial investment costs. Providing technical training through workshops, demonstration farms and extension services will equip farmers with the necessary skills for system operation, maintenance and troubleshooting. Developing affordable and modular RAS designs that allow for gradual upgrades based on farmers' financial capacities can further encourage adoption. Additionally, promoting energy-efficient strategies—such as the use of solar-powered aerators and pumps—can help reduce operational costs and enhance sustainability. Finally, fostering community-based approaches by establishing cooperative groups for shared RAS infrastructure and knowledge exchange can improve system management and ease the transition for farmers.

Fig. 5: The filter system is currently in use at the neon tetra farm.

Conclusions

In the main production center of neon tetra in Indonesia, particularly in Bojongsari District, Depok, farming is generally conducted by small-scale farmers using stagnant water systems. Despite challenges such as urbanization, limited land availability, disease outbreaks and declining water quality, neon tetra (*Paracheirodon innesi*) production in Indonesia has strong potential for improvement through the application of appropriate technology. Zero-water exchange recirculating systems (ZWERS) offer increased production efficiency and support sustainable aquaculture. The implementation of ZWERS in neon tetra farming allows stocking densities up to three times higher than those of conventional stagnant water systems commonly used by local farmers. This system maintains water quality parameters and does not significantly affect the survival or growth of neon tetra. However, the widespread adoption of ZWERS among neon tetra farmers requires technical training, infrastructural improvements and financial support.

References

1. Novák J, Kalous L, Patoka J. Modern ornamental aquaculture in Europe: Early history of freshwater fish imports. Rev Aquac 2020;12:2042–60.
2. Dey VK. The global trade in ornamental fish [Internet]. 2016 [cited 2024 Aug 28];52–5. Available from: https://www.bassleer.com/ornamentalfishexporters/wp-content/uploads/sites/3/2016/12/GLOBAL-TRADE-IN-ORNAMENTAL-FISH.pdf
3. Chapman FA, Fitz-Coy SA, Thunberg EM, Adams CM. United States of America trade in ornamental fish. J World Aquac Soc [Internet] 1997;28(1):1–10. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1749-7345.1997.tb00955.x
4. Saputro A, Farmayanti N, Diatin I. Analisis strategi bisnis ekspor ikan hias air tawar (kasus di PT NAE, Jakarta). Buletin Ekonomi Perikanan 2007;7(1):50–63.
5. Setiyowati H, Nugroho M, Halik A. Developing a blue economy in Depok West Java, Indonesia: Opportunities and challenges of neon tetra fish cultivation. Sustainability 2022; 14(20):13028. https://www.mdpi.com/2071-1050/14/20/13028
6. Nurlaili N, Hikmah H, Wijaya R, miftakhul huda H. Potential and problems of ornamental fish farming development in Depok City (case study: neon tetra, cardinal and red nose ornamental fish farmer in Bojongsari District). IOP Conf Ser Earth Environ Sci 2021;718:12072.

7. Mayoza L, Suryana A, Lili W, Rizal A. Analytical Business Development on Neon Tetra (Paracheirodon innesi) Ornamental Fish Cultivation. global scientific journal 2018; 6(7):938–45.

8. DKP3. Laporan statistik produksi perikanan budidaya ikan hias dan nilainya menurut jenis ikan (ikan hias). Depok. Pemerintah Kota Depok. Depok: 2018.

9. Bittencourt SP, Machado NV, Marshall B, Hrbek T, Farias I. Phylogenetic relationships of the neon tetras *Paracheirodon* spp. (Characiformes: Characidae: Stethaprioninae), including comments on *Petitella georgiae* and *Hemigrammus bleheri*. Neotrop Ichthyol 2020;18.

10. Weitzman SH, Fink WL. Neon Tetra relationships and phylogenetic systematics. Tropical Fish Hobbyist 1987;36(2):72–77.

11. Kusumah RV, Priyadi A, Yamin M, Ardi I. Best Management Practice Produksi Benih Ikan Hias Neon Tetra (Paracheirodon innesi) di Indonesia. Conference: Seminar Nasional Tahunan XIX Hasil Penelitian dan Perikanan 2022 At: Yogyakarta, 2022;111–20. Available from: https://www.researchgate.net/publication/364985509

12. Musthofa SZ, Alimuddin A, Arfah H, Sulistyowati DT, Carman O, Kusrini E. Morphometric And Molecular Variation Of Neon Tetra Fish (*Paracheirodon innesi*) From Bojongsari District, Indonesia. Indonesian Aquaculture Journal 2025; 19(2):133. https://ejournal-balitbang.kkp.go.id/index.php/iaj/article/view/14132

13. Kusumah RV, Fahmi M, Alimuddin A, Soelistyowati D. Variations of red color coverage of cultured neon tetra (*Paracheirodon innesi*) for breeding improvement strategies. Indonesian Aquaculture Journal 2021; 16:1–11.

14. Sugiani D, Purwaningsih U, Gardenia L, Mufidah T, Nafiqoh N, Aryati Y, et al. A case study on mortality of neon tetra (*Paracheirodon innesi*) associated with the seasonal climate transitions in West Java – Indonesia. IOP Conf Ser Earth Environ Sci 2020; 521(1):12022. https://dx.doi.org/10.1088/1755-1315/521/1/012022

15. Fatima S, Komal W, Minahal Q, Munir S, Liaqat R, Amman H. Effect of stocking density on fish growth and feed conversion ratio: A review. Int J Biosci 2020; 17(2):1–8.

16. Millot R, Demolliens M, Filippi JJ, Pugliese S, Delmas A, Boussard A *et al*. Effect of stocking density on survival and growth of brown meagre

Sciaena umbra (l.) larvae. Fishes 2024; 9(6).

17. Lavilla CR. Disease development. In Lio-Po GD, C.R. Lavilla CT, Cruz-Lacierda ER, editor. 2001. Health management in aquaculture (pp. 1-8). Tigbauan, Iloilo, Philippines: 2001.
18. Suantika G, Azizah F, Muhammad H, Aditiawati P, Lumbantoruan G. Performance of zero water discharge (ZWD) system with nitrifying bacteria and microalgae *Chaetoceros calcitrans* components in super intensive white shrimp (*Litopenaeus vannamei*) culture. J Aquac Res Dev 2015; 06(09):1–6.
19. Şahin T, Üstündağ C. Effect of different rearing systems on survival rate of hatchery reared black sea turbot, *Scophthalmus maximus*. Turk J Fish Aquat Sci 2003; 3:25–8.
20. De león-Ramírez J, García-Trejo J, Felix-Cuencas L, López-Tejeida S, Sosa-Ferreyra CF, González-Orozco A. Effect of the water exchange rate in a recirculation aquaculture system on growth, glucose and cortisol levels in *Oreochromis niloticus*. Lat Am J Aquat Res 2022; 50(2):267–75.
21. Kristan J, Blecha M, Policar T. Survival and growth rates of juvenile grass carp *Ctenopharyngodon idella* overwintered in ponds and recirculating aquaculture systems including a comparison of production economics. 2019; 261–6.
22. Astari B, Budiardi T, Ismi S, Effendi I, Hadiroseyani Y. Increasing the stocking density of grouper nurseries for aquabusiness efficiency in recirculating aquaculture system (RAS) with bioremediation. Hayati [Internet] 2022; 30(2):198–206. https://journal.ipb.ac.id/index.php/hayati/article/view/40236
23. Maher H, Azab AM, Radwan IA, Husein MSHA. Comparison between recirculating aquaculture system (RAS) ponds and earthern aquaculture ponds in overwintering juveniles of the nile tilapia, *Oreochromis niloticus*. Egypt J Aquat Biol Fish 2023; 27(1):531–45. https://ejabf.journals.ekb.eg/article_288512_27a070074ac9f140fb9c638a3b8467f2.pdf
24. Islam MA, Uddin MH, Uddin MJ, Shahjahan M. Temperature changes influenced the growth performance and physiological functions of Thai pangas *Pangasianodon hypophthalmus*. Aquac Rep 2019;13.
25. Lindmark M, Audzijonyte A, Blanchard JL, Gårdmark A. Temperature

impacts on fish physiology and resource abundance lead to faster growth but smaller fish sizes and yields under warming. Glob Chang Biol 2022; 28(21):6239–53.

26. Rodrigues-Filho JL, Abe DS, Gatti-Junior P, Medeiros GR, Degani RM, Blanco FP *et al*. Spatial patterns of water quality in Xingu River Basin (Amazonia) prior to the Belo Monte dam impoundment. Brazilian Journal of Biology 2015; 75(3):S34–46.
27. Chapman FA, Colle DE, Rottmann RW, Shireman J V. Controlled spawning of the neon tetra. Progressive Fish-Culturist 1998; 60(1):32–7.
28. Kadtan N, Shillewar KS. Reproduction of neon tetra (*Paracheriodon Innesi*) under controlled conditions. Int J Life Sci Res 2023;11(1):10–4.
29. Kucharczyk D, Targońska K, Żarski D, Krejszeff S, Kupren K, Łuczyński MJ *et al*. The reproduction of neon tetra,*Paracheirodon innesi* (myers, 1936), under controlled conditions. Pol J Nat Sci 2010; 25(1):81–92.
30. Aich N, Nama S, Biswal A, Paul T. A review on recirculating aquaculture systems: challenges and opportunities for sustainable aquaculture. Innovative Farming 2021; 5(1):17–24. https://innovativefarming.in/index.php/IF/article/view/109.
31. Velichkova K, Sirakov I. The usage of aquatic floating macrophytes (*Lemna* and *Wolffia*) as biofilter in recirculation aquaculture system (RAS). Turk J Fish Aquat Sci 2013; 13:101–10.
32. Xiao R, Wei Y, An D, Li D, Ta X, Wu Y *et al*. A review on the research status and development trend of equipment in water treatment processes of recirculating aquaculture systems. Rev Aquac 2019; 11(3):863–95. https://onlinelibrary.wiley.com/doi/abs/10.1111/raq.12270
33. Ali B, Anushka, Mishra A. Effects of dissolved oxygen concentration on freshwater fish: A review. Int J Fish Aquat Stud 2022;10(4):14.
34. Rahman M, Haidar M, Khan M, Rahman M, Mahmud Y. Mass Mortality of Fishes: A catastrophic phenomena at Haor regions in Bangladesh. Bangladesh J Fish Res 2018;17 (1-2)(1–2):101–6.
35. Supriyono E, Adiyana K, Thesiana L. A study of environmentally friendly recirculating aquaculture system on lobster *Panulirus homarus* nursery. Pol J Environ Stud 2023; 32(5):4805–11. https://doi.org/10.15244/pjoes/166596

36. Losordo T, Masser M, Rakocy J. Recirculating aquaculture tank production systems an overview of critical considerations. SRAC 1998; 451:1–5.

37. Gomez Isaza DF, Cramp RL, Franklin CE. Thermal plasticity of the cardiorespiratory system provides cross-tolerance protection to fish exposed to elevated nitrate. Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology. 2021; 240:108920. https://www.sciencedirect.com/science/article/pii/S1532045620302209

38. Berry KLE, Hess S, Clark TD, Wenger AS, Hoogenboom MO, Negri AP. Effects of suspended coal particles on gill structure and oxygen consumption rates in a coral reef fish. Mar Pollut Bull 2021; 169:112459. https://www.sciencedirect.com/science/article/pii/S0025326X21004938

39. Das T, Young BC. Biofilm formation by pathogenic bacteria: the role of quorum sensing and physical - chemical interactions. In: Theerthankar D, editor. Focus on Bacterial Biofilms. Rijeka: IntechOpen; 2022. page Ch. 3. https://doi.org/10.5772/intechopen.106686

40. Nayak SK. Multifaceted applications of probiotic *Bacillus* species in aquaculture with special reference to *Bacillus subtilis*. Rev Aquac 2020; 13(2):862–906.

41. Abd El-Rhman AM, Khattab YAE, Shalaby AME. Micrococcus luteus and Pseudomonas species as probiotics for promoting the growth performance and health of Nile tilapia, Oreochromis niloticus. Fish Shellfish Immunol 2009; 27(2):175–80.

42. Morozova MA, Gorovcov AV, Prazdnova EV, Basankina VM, Chistyakov VA, Pepoyan A *et al*. Bacteria of genus Bacillus as antagonists of pathogens in aquaculture. Vestnik of Astrakhan State Technical University Series: Fishing industry 2023; 2023(1):89–97.

43. Mohapatra S, Chakraborty T, Prusty AK, Das P, Prasad K, Mohanta K. Use of different microbial probiotics in the diet of rohu, *Labeo rohita* fingerlings: Effects on growth, nutrient digestibility and retention, digestive enzyme activities and intestinal microflora. Aquac Nutr 2011; DOI: 10.11.

44. Chen H, Moraru CI, Protasenko V V. Maximizing the disinfection effectiveness of 254 nm UV-C light with a special design unit: simulation and experimental approaches. Front Food Sci Technol 2023;

3(:1223829.).
https://www.frontiersin.org/articles/10.3389/frfst.2023.1223829

45. Sandri A, Tessari A, Giannetti D, Cetti A, Lleo MM, Boschi F. UV-A radiation: Safe human exposure and antibacterial activity. Int J Mol Sci 2023; 24(9):8331.

46. Singh P, Pradesh U, Deen P, Upadhyaya D, Chikitsa P, Vishwavidy *et al*. Production Cost and Productivity Analysis of Singhi (Heteropneustes fossilis) Under Advance and Low Cost Recirculatory aquaculture systems (RAS) of Haryana. Agro Economist - An International Journal 2023; 10 (03):(03):01–8. https://www.researchgate.net/publication/374898223

9

CHAPTER

Recirculating Aquaculture System for Hatchery of Tor Soro (Valenciennes, 1842) in Indonesia

Jojo Subagja, Otong Zenal Arifin, Wahyulia Cahyanti, Reza Samsudin
Research Center for Applied Zoology, National Research and Innovation Agency Indonesia (BRIN)

Idil Ardi
Research Center for Freshwater Aquaculture, National for Research and Innovation Agency (BRIN), Indonesia

Muhammad Hunaina Fariduddin Ath-thar*
Research Center for Applied Zoology, National Research and Innovation Agency Indonesia (BRIN)

Corresponding Author: mh.fariduddin.aththar@brin.go.id

Abstract

Aquaculture is among the most efficient methods for producing aquatic-derived food. To ensure its sustainable development and address existing challenges, the Recirculating Aquaculture System (RAS) has emerged as a promising approach. RAS is a fish production system operated in a fully controlled environment that enables continuous water recycling and reuse. This technology represents a significant advancement in inland fisheries, offering several advantages over conventional fish farming methods. In Indonesia, RAS technology for freshwater aquaculture has been widely applied to species such as koi (*Cyprinus rubrofuscus*), catfish (*Clarias* spp.), tilapia (*Oreochromis* spp.) and pangasius (*Pangasianodon hypophthalmus*). Trials with local freshwater species have also been conducted, including *Tor soro* and baung (*Hemibagrus nemurus*). This chapter presents a detailed description of the RAS design and operation for the hatchery production of *Tor soro*. The discussion includes facility layout, system installation and performance evaluation through water quality monitoring and growth trials of *Tor soro* under RAS conditions.

Keywords: *Tor soro*, water recirculation system, RAS installation, water quality, fish growth

Introduction

The rapid increase in the human population has led to a growing demand for food. Meanwhile, the climate and environmental crisis are worsening day by day. This situation highlights the urgent need for innovative solutions to secure a stable food supply and sustainable energy sources. Aquatic food sources, both freshwater and marine, are crucial in advancing global food security and nutrition goals, while also offering a more environmentally friendly alternative compared to terrestrial animal food sources [1]. Aquaculture is one of the efficient methods for producing aquatic-based food. To support the development of aquaculture today and in the future while addressing existing challenges, the Recirculating Aquaculture System (RAS) is seen as highly representative.

RAS is a fish production system with a fully controlled environment that recycles and reuses water [2]. RAS is one of the technological breakthroughs that is currently being actively developed in the field of inland fisheries, considering several advantages that this system has over conventional fish farming methods. Some of the benefits include water conservation, ease of control and monitoring, the ability to produce year-round and the need for less land. This system is particularly effective in hatchery units that have limited water resources. In this system, the water used in cultivation is processed through various filtration and treatment stages before being reused. RAS allows optimal control over environmental factors such as temperature, water quality and feed distribution, which ultimately enhances fish growth and survival rates. Additionally, this system also provides significant environmental benefits by reducing water consumption and minimizing the disposal of organic waste [3]. RAS can save up to 90% of water use compared to conventional farming systems while maintaining or even increasing productivity [4]. Therefore, RAS not only enhances production efficiency but also plays a role in promoting more sustainable aquaculture practices.

RAS technology can be applied in both brackish water and marine aquaculture, but it is more commonly used in freshwater farming. This system is suitable for various types of fish, both established commodities and newly domesticated species. The technology of RAS and the process of fish domestication are closely related, where applying RAS to the domestication of local freshwater fish allows for more intensive and controlled production to obtain specific characteristics and increase economic value. The use of RAS in local fish farming in Indonesia is a cutting-edge solution that is efficient, water-saving and environmentally friendly, while allowing for optimal water quality control and higher production potential.

The use of RAS technology for freshwater fish in Indonesia has been widely implemented. Recent studies, for example, on Koi fish [5], catfish [6], tilapia [7] and Patin fish [8], as well as many other common commodities. Meanwhile, for local freshwater fish in Indonesia, RAS technology has been tested on several species, such as *Tor soro* [9, 10] and Baung fish [11]. In this chapter, the details of recirculating aquaculture system for hatchery of *Tor soro* will be described including building and layout, RAS installation and running of RAS system.

The building and layout for RAS of *Tor soro*

The indoor RAS for *Tor soro* offers several advantages: (1) it regulates temperature, water quality and feeding to optimize fish growth; (2) it requires minimal water and energy compared to conventional aquaculture; and (3) it has a smaller land footprint with reduced waste and pollution. Consequently, indoor RAS fish farming mitigates environmental degradation. By creating an optimal climate for fish growth and survival, RAS ensures controlled feeding, high water quality through filtration and minimal disease or parasitic risks, thereby enhancing fish health and productivity.

The layout drawing show the detail structure of the facility and size and quantity of support materials needed to ensure stability of the facility. The hatchery unit has a building area of 660 m^2, with a width of 20 meters and a length of 33 meters (Figure 6). The facility's equipment includes:

- 10 fiberglass tanks with a volume of 7 m^3 each
- 6 fiberglass tanks with a volume of 5 m^3 each
- 3 water storage tanks, each with a volume of 1 m^3
- 36 aquariums measuring 50 × 50 × 75 cm
- 1 set aquarium rack

Fig 6: Hatchery building. A: Hatchery building from outside, B: The entrance to hatchery building and preview of the inside of hatchery building

The facility's equipment will be set up into several units, including recirculating system unit for larva rearing, recirculating system unit for grow-out and broodstock maintenance, quarantine/adaptation unit and additional biological filters for the fiberglass tanks. The layout plan for hatchery units is shown in Figure 7.

Larva Rearing Unit

The larva rearing unit consists of 36 aquariums, each with a water capacity of 170 liters (Unit A; Figure 7 and Figure 8). The aquariums are placed on racks, with each rack supporting three aquariums. Each aquarium is equipped with a 1-inch threaded outlet hole, which connects to a 3-inch PVC collector pipe. The wastewater flows into the biological filter by gravity, following a slope of 4.5 degrees and enters the biological filter and sand filter. Filtered water flows into the final compartment and is then drawn by a 0.75 HP pump, which directs it to a V200 sand filter before entering the storage tank positioned at a height of 2.75 meters. Water from the storage tank is distributed by gravity to all aquariums using a 1.5-inch collector pipe, with stop valves (1.5 inches) installed at each endpoint. The storage tank is also equipped with an overflow drainage system connected to the last filter compartment. Each aquarium is fitted with a single aeration point. The layout of the larvae rearing unit is shown in Figure 8.

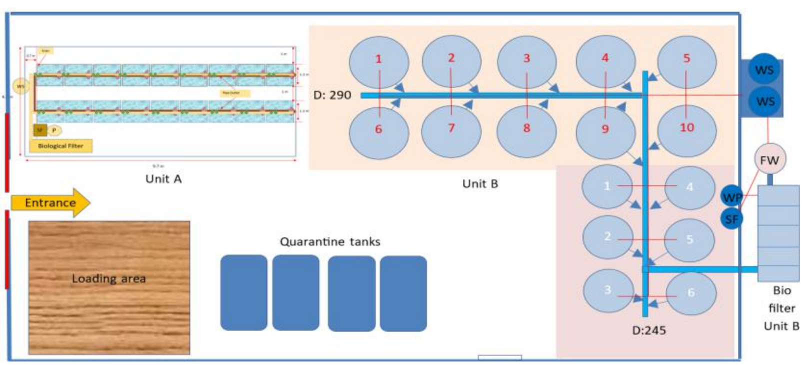

Fig 7: Design layout of the Tor soro hatchery. Unit A: Larva rearing unit, Unit B: Broodstock and maintenance unit, red line: filtered water flow to the tank, Blue line: wastewater from the tank, 1-10 (Red): Grow-out tank, 1-6 (white): Broodstock tank, WP: Water pump, SF: Sand Filter, FW: Filtered Water. The wastewater flows (blue line) into the biological filter by gravity and enters the biological filter and sand filter, then drawn by a pump, which directs it a sand filter before entering the storage tank. Water from the storage tank is distributed to all aquariums.

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Broodstock maintenance and grow-out unit

The Broodstock Maintenance Unit consists of 10 cylindrical fiberglass tanks with a capacity of 7,000 liters each, while the grow-out unit consists of 6 cylindrical fiberglass tanks with a capacity of 5,000 liters each (Unit B; Figure 9). All drainage outlets from each tank use 2-inch pipes, which are connected to a 3-inch outlet collector pipe, leading to the first stage of the filter tank.

Fig 8: Layout of the larva rearing unit (Unit A) with 36 aquariums. SF: Sand filter, WP: water pump, WS: Water storage. Red line: filtered water flow to the tank, yellow line: wastewater from the aquarium. The wastewater flows (yellow line) into the biological filter by gravity and enters the biological filter and sand filter, then drawn by a pump, which directs it a sand filter before entering the storage tank. Water from the storage tank is distributed to all aquariums.

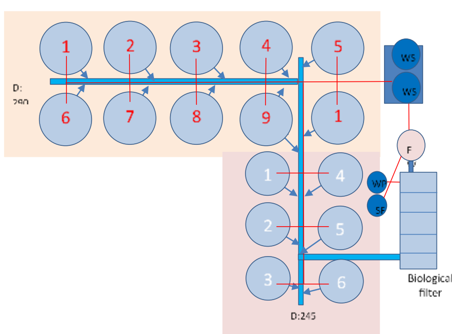

***Fig 9:** Layout of the broodstock and grow-out unit (Unit B) with 10 and 6 tanks, respectively. 1-10 (Red): grow-out tank, 1-6 (white): broodstock tank, D: tank diameter, WS: water storage, P: water pump, FW: filtered water, P: Water pump. The wastewater flows (blue line) into the biological filter by gravity and enters the biological filter and sand filter, then drawn by a pump, which directs it a sand filter before entering the storage tank.*

Quarantine and acclimatization unit

The quarantine unit consists of 4 fiberglass tanks with dimensions of LxWxH 2.5x1.5x0.7 meters. Each tank is connected to its own filter (one tank to one filter). The filtered water is transferred using a pump with a capacity of 60 watts. The biological filter uses 30% bio balls, 40% coral rubble and 30% used nets by volume. Each maintenance tank is equipped with two aeration points.

RAS Installation for Larvae Rearing Unit

Installation of aquariums

The aquarium for larvae rearing has a dimension of 100 x 40.8 x 50 cm (LxWxH) (Figure 10). The material for the aquarium is glass. Each aquarium was drilled on one of its long sides, with the hole positioned 10 cm from the side edge and 10 cm from the top edge.

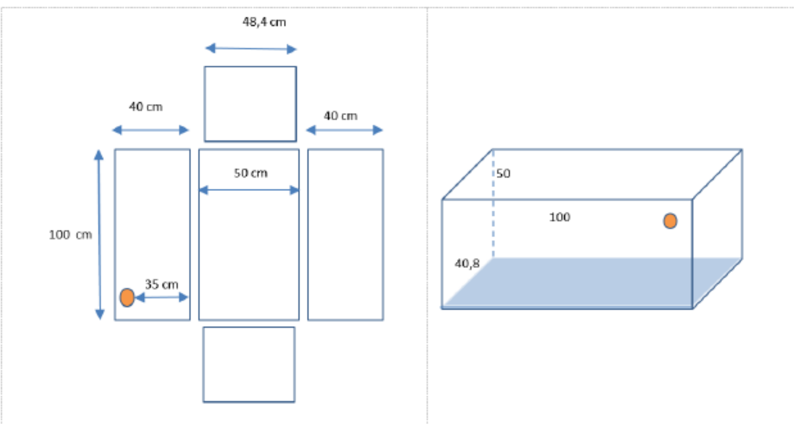

Fig 10: The dimension of aquaria for Tor soro larvae rearing in centimeter (cm)

The aquarium rack layout was arranged with the larva rearing unit positioned at the front left side of the hatchery, near the main entrance. The sketch and dimensions of the racks are detailed in Figure 11. The racks were assembled in four rows (two pairs), with each row consisting of three racks and each rack accommodating three aquariums—totaling nine aquariums per row. The first and second rows formed the left and right sections, both receiving access to clean water inlet pipes and wastewater outlet pipes. The same setup was applied to the second pair of rows. The installation process for the aquarium racks is illustrated in Figure 12.

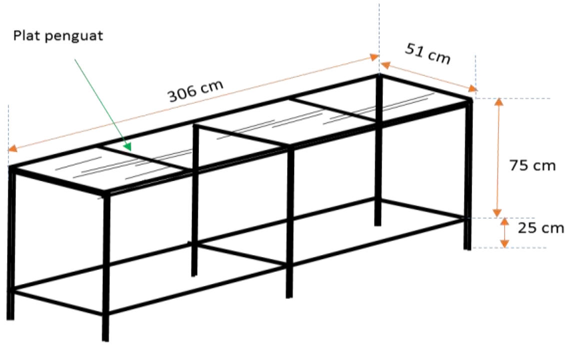

Fig 11: Design/sketch of rack and aquarium

Fig 12: Arrangement of aquarium racks, including the installation of a base using plywood and Styrofoam

The next step was the arrangement of the aquariums. The aquariums were then arranged lengthwise to fit the racks properly. The final arrangement aquariums on racks with plywood and styrofoam base process is illustrated in Figure 13.

Fig 13: Aquariums on racks with plywood and Styrofoam base

The piping installation

The piping installation for the larva rearing unit began with the construction of the outlet pipe system from the aquariums (Figure 14). Each drilled hole in the aquarium was fitted with an external and internal threaded socket for a 1-inch pipe. On the outside, the threaded socket was connected to a 3-inch collector pipe. Inside the aquarium, a 1-inch pipe was attached to the socket and connected through an L-boh fitting, which functioned as a siphon system to remove waste from the bottom of the aquarium.

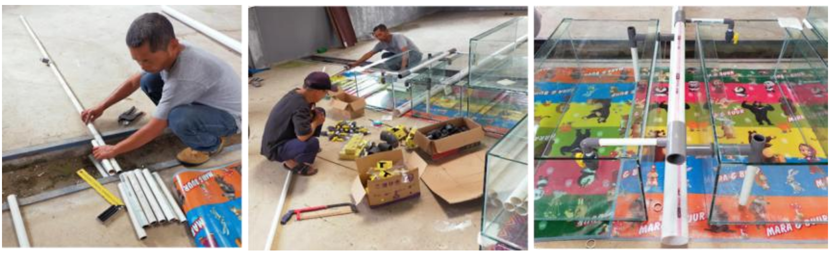

Fig 14: Preparation of inlet and outlet pipe components for aquariums

Clean water from the storage tank was distributed to all aquariums by gravity flow using a 1.5-inch PVC pipe. The main pipe was then split into two channels, with each channel supplying two rows of aquariums. At the end of each distribution branch, a ½-inch stop valve was installed to control water flow. The inlet pipe was positioned opposite the drainage hole in each aquarium to ensure efficient water circulation. The setup is illustrated in Figure 15.

Fig 15: Installation of aquarium inlet pipes

The collector pipes were installed using 3-inch PVC pipes, positioned below the aquariums between the two rows of racks (Figure 16). Each pipe was set at a 5% slope, running from one end of the rack to the other to ensure smooth drainage. This setup was mirrored for the other collector pipes. At the lowest end, the two collector pipes were connected using a 3-inch L-boh fitting

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on the outermost pipe and a 3-inch T-fitting in the center. Once joined, one end of the combined pipe directed wastewater into the first compartment of the filter tank.

Fig 16: Installation of collector pipes for collecting wastewater from all aquariums

Water pump, biofilter and water storage installation

Water quality is a critical factor in hatchery operations and must be routinely monitored for key physic-chemical parameters, including salinity, pH, nitrite-nitrogen ($N\text{-}NO_2$) and temperature. The larva rearing unit used a 0.75 HP water pump with 1.5-inch inlet and outlet pipes. The pump was installed outside the 5th compartment of the filter tank. The pump inlet pipe was fitted through one of the walls of compartment 5, using an external-internal threaded socket for a secure connection. At the end of the inlet pipe, a 1.5-inch foot valve was installed to prevent backflow and maintain consistent water intake. Turbid water discharged from sand filters often contains bacteria due to the passage of detritus, microorganisms and debris under high pressure. To prevent this, the initial water flow through the filter be drained in compartment 5 for 20–30 minutes or until it runs clear.

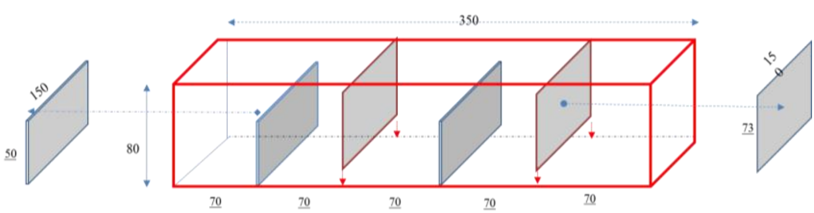

Fig 17: The sketch of biofilter with five compartments

The biological filter uses a fiberglass tank with dimensions (L × W × H) of 1.5 × 1.0 × 0.5 meters, consisting of five compartments. Three middle compartments function as biological filters, while the two outer compartments remain unfiltered. The biological filter design is shown in Figure 16. The biological filter occupied the 2nd to 4th compartments of the filter tank (Figure 17) with materials consisting of 60% coral rocks, 30% bio balls and 10% nets.

The base of each filter compartment was lined with bamboo grates, secured with 4x6 cm wooden beams for structural support. A layer of netting was placed over the grates before adding the biofilter materials up to a designated height (Figure 18).

Fig 18: Installation of biofilter and connector pipes to the pump, sand filter, water storage and collector outlet pipes from the aquariums

The sand filter V200 was installed as the final filtration stage. Water drawn by the pump was directed into the sand filter, where it was purified before being pushed into the storage tank, which was positioned at a height of 2.75 meters (Figure 18). The sand filter featured a "mountain valve" with five operational settings:

1. Filtration – Normal filtering mode
2. Running – Standard operation
3. Rinse – Cleans the filter media
4. Backwash – Flushes out accumulated debris
5. Close – Shuts off flow

On the side of the mountain valve, there were three threaded 1.5-inch pipe connections:

- Pump – Water intake from the pump
- Return – Clean water outlet to the water storage
- Wash – Wastewater discharge for cleaning

Additionally, an amperemeter was installed to monitor pressure levels. A diagram of the mountain valve setup is shown in Figure 19.

Fig 19: Position of the inlet pipe from the fifth shelter, connection from the pump to the sand filter. A: Water inlet from biological filter to water pump, B: Water pump to sand filter, C: Clean water from sand filter to water storage, D: Back wash or disposal water from sand filter

Fig. 20: Sand filter V200, mountain valve, ampere meter and connector pipes

The storage tank was a 500-liter cylindrical fiberglass container. Two 1.5-inch threaded pipe sockets were installed at the base of the water storage, each serving a different function: 1) Overflow outlet to return excess water to the 5th compartment of the filter tank and 2) Inlet collector pipe to supplies clean water to the aquarium system. Water from the pump entered the water storage from the highest point to ensure proper distribution.

Aeration

To increase the oxygen levels in the maintenance medium, two Hi-Blow aeration pumps with a capacity of 100 watts are used. One pump is dedicated to aerating the broodstock and growth-out units (aerating 16 tanks) as well as 4 quarantine units, while the other pump is used for aerating the larval rearing aquarium unit. The air pump outlets use 1.5-inch PVC pipes, which are distributed to the tanks using air valves and 1/4-inch plastic hoses. At the end of the hoses, the "uniring" flexible nano bubble tubes with an outer diameter of 16 mm and an inner diameter of 10 mm are installed, which function as bubble breakers (Figure 19 and 21).

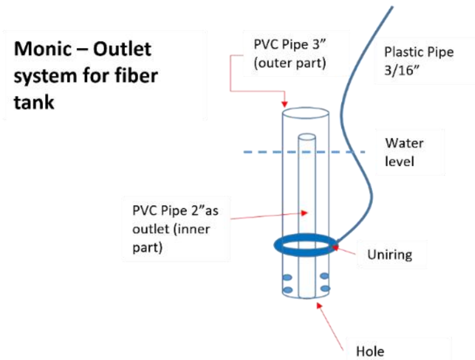

Fig 21: Sketch of aeration in the rearing tank using uniring nano bubble installed on the monic outlet pipe

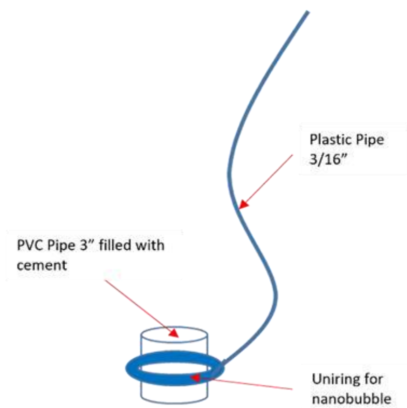

Fig 22: Sketch of aeration in the aquarium rearing unit using a weighted polyvinyl carbonate (PVC) pipe filled with cement mixture

Oxygenation was provided by capturing free air using a HiBlow air pump with a 100-watt capacity. The compressed air was distributed to the rearing tanks through a ½-inch PVC pipe network. Each tank was equipped with one aeration point, controlled by an air valve installed on the distribution pipe. The air was delivered via plastic tubing and to generate fine air bubbles, a Uniring nano bubble diffuser was used, secured with a weight to keep it submerged at the desired depth.

Fig 23: Installation of air distribution pipes from hi-blow, faucet installation and fabrication of "uniring bubble" air diffuser

RAS Installation for Broodstock Maintenance and Grow-out Unit

The initial step for broodstock and grow-out installation was rearranging the layout of the fiberglass tanks (Figure 24). Ten 7 m^3 tanks were organized in two parallel rows along the length of the building, positioning them at the back left corner. The spacing between the tanks was carefully adjusted to facilitate the installation of water and aeration systems efficiently. Meanwhile, six 5 m^3 tanks were arranged in three rows perpendicular to the building's length. The final layout formed an inverted L-shape, as illustrated in Figure 7 and 9.

Fig 24: Construction of uniring nano bubble weights: 3-inch PVC pipe, 5 cm height, filled with sand-cement mixture and the generated air bubbles

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Fig 25: Arrangement of fiberglass tank for broodstock and grow-out unit

After the formation was arranged, the next step was the installation of the wastewater outlet system (Figure 20). Each fiberglass tank was equipped with a 1.5-inch pipe fitted with a stop valve. The ends of these pipes were connected to a 3-inch collector pipe, which was installed centrally between the rows of tanks, positioned above the floor surface. The collector pipe directed the wastewater to a filter tank located outside the hatchery building, leading into the first compartment of the filter tank system.

Fig 26: Installation process of outlet pipes and collector pipes in the broodstock and grow-out unit

Biofilter unit installation

The biological filter unit in this system is made of fiberglass with dimensions (L × W × H) of 3 × 1.5 × 0.8 meters. It consists of five compartments: the three middle compartments function as biological filters, while the two outer compartments are left without filters. A sketch of the biological filter is shown in Figure 5. Filtered water is drawn by a 1 HP pump and directed into a V500 sand filter tank via a 1.5-inch PVC pipe. The water is then pumped into a 500-liter water storage tank positioned at a height of 3.5 meters. Clean water from the storage tank is distributed to each fiberglass tank through a 1.5-inch collector pipe, with individual distribution using ½-inch pipes.

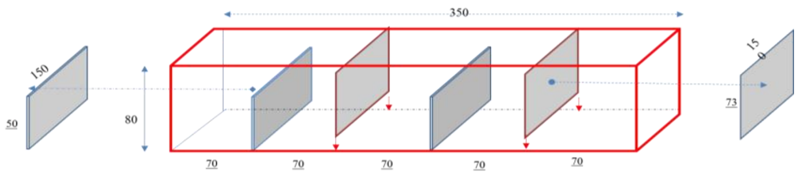

Fig 27: Sketch of the biological filter tank with five compartments in the broodstock rearing unit and grow-out rearing unit

The biofilter for the broodstock maintenance unit was placed outside the hatchery building. The fiberglass filter tanks were embedded into the ground so that the top edge of the filter tank was positioned just below the outlet collector pipe—slightly lower than the hatchery floor level. Compartments 2 to 4 were filled with biofilter materials, including used nets, coral rocks and bio balls (Figure 27). At the base of each of these three filter compartments, bamboo grates were first installed, supported by 4x6 cm wooden beams to provide structural stability.

Fig 28: Installation of filter tank in the broodstock rearing unit

Water Pump and Sand Filter V500 Installation

The water pump and sand filter were installed inside the building to protect them from rain and direct sunlight. The pump's suction pipe was connected to the 5th compartment of the filter tank using a 1.5-inch PVC pipe. The pump outlet was then connected to the sand filter, where the water was purified before being pumped up into the storage tank.

Clean water from the water storage was distributed by gravity flow to the maintenance tanks through 1.5-inch PVC pipes. Additionally, a portion of the water from the water storage was redirected back to the filter tank via an overflow outlet, ensuring continuous filtration and water circulation (See Figure 29).

Fig 29: Installation of pump and sand filter in the broodstock rearing unit (left and center) and inlet pipe distribution to each tank (right)

Running of RAS system for *Tor soro*

Principles of the recirculating system and biofilter conditioning phase

The recirculating system consists of several key components: the culture tank/growing tank, which serves as the primary rearing unit sized appropriately based on stocking density; the particle filtration unit, which removes suspended solid waste to prevent clogging of the biofilter and excessive oxygen consumption; the biofilter unit, the core component of the system responsible for the nitrification process, where beneficial bacteria convert toxic ammonia into less harmful compounds; the water recirculation pump, which ensures water movement throughout the system, lifting and directing flow as required; and the air pump, which supplies oxygen to maintain adequate dissolved oxygen levels in the culture medium.

The water flow mechanism in the biofilter recirculating system starts with the filling phase, where all tanks and reservoirs are filled with water sourced from a groundwater pump, distributing it into the filter tanks (shelter), water storage and rearing units until full. Once the recirculation pump is activated, water is drawn from the 5th filter compartment, creating a lower water level than in the 1st compartment. This causes water to flow naturally by gravity through the 2nd, 3rd and 4th filter compartments, driven by the height difference. The pump then pushes the water through the sand filter, where it undergoes final filtration before entering the storage tank. From the storage tank, water is distributed by gravity into the rearing tanks. The waste removal process begins as outlet pipes from the rearing tanks collect feces and uneaten feed, directing the wastewater into the collector pipes, which lead back to the filter compartment 1. For better efficiency, a mechanical filter should be installed in compartment 1 to trap large debris and prevent clogging of the biofilter. The mechanical filter should be easy to clean to ensure smooth operation.

The biofilter functions as a bioreactor, breaking down organic waste and ammonia through the nitrification process, involving autotrophic bacteria such as *Nitrosomonas*, *Nitrosococcus*, *Nitrospira*, *Nitrosolobus* and *Nitrosovibrio*, which convert ammonia (NH_3) into nitrite (NO_2^-). Additionally, nitrite-oxidizing bacteria like *Nitrobacter* further convert nitrite (NO_2^-) into nitrate (NO_3^-), a less toxic compound. Some heterotrophic bacteria also assist in ammonia oxidation and nitrification [12, 13]. If oxygen is insufficient, denitrification may occur, leading to the production of harmful nitrogen compounds. To prevent this, aeration should be added in the biofilter unit to maintain oxygen levels.

To optimize biofilter efficiency, the water contact time and surface area of the filter media must be maximized. The efficiency of the biofilter depends on how long the water interacts with the filter media and the surface area available for bacterial colonization. Adjusting the flow rate of water into compartment 1 from the collector pipe ensures optimal contact time. If the flow rate into each aquarium is reduced, water accumulates in the storage tank, raising its water level. Once the water reaches the overflow pipe, it spills into compartment 5, ensuring balanced recirculation. The overflow pipe acts as a buffer to match the pump's intake rate and optimizes biofilter performance by preventing excessively short water retention times, ensuring efficient waste breakdown. This continuous water cycling and filtration creates a stable and self-sustaining environment, maintaining water quality while supporting fish health and growth.

The capacity utilization of the system

The capacity utilization of the indoor hatchery system includes two Recirculating Aquaculture Systems (RAS). One of these is a larva rearing unit equipped with 36 aquariums, each holding 170 liters of water. This system supports larvae rearing up to the juvenile stage (3-4 cm), with a minimum production capacity of 60,000 fish per month. Additionally, this unit is well-suited for experimental research, as the number of available tanks provide flexibility for scientific trials and controlled studies. For the next stage of rearing, juveniles can continue to be grown indoors using fiberglass tanks with a capacity of 5 m^3 each. The 60,000 juveniles produced from the larva rearing unit can be effectively housed in six tanks for further growth. The broodstock maintenance unit utilizes ten fiberglass tanks, each with a 7 m^3 capacity, totaling 70 m^3. This setup can support 200 kg of broodstock biomass, ensuring optimal conditions for spawning and reproduction. Additionally, the facility includes a fish quarantine unit, consisting of four fiberglass tanks, each with a 1.5 m^3 water volume. These tanks serve as acclimatization units for newly arrived fish before their transfer to the main RAS system for further rearing.

The evaluation of the success or productivity of the completed system can be conducted once it is put into operation for rearing. Monitoring the functionality of components and measuring key water quality parameters—such as ammonia, nitrate and pH—is essential throughout the rearing process. By the end of the evaluation, the collected data will provide a foundation for developing an operational manual for the RAS system.

Water quality check of RAS for Tor soro

The use of a recirculating aquaculture system (RAS) influences water quality in *Tor soro* culture. Observations showed notable differences in water quality parameters between RAS and conventional earth pond systems. Key parameters that varied included dissolved oxygen (DO), temperature, pH, ammonia and alkalinity. In RAS tanks, DO levels remained relatively stable, ranging from 5.87 to 6.23 mg/L. In contrast, DO levels in the earth pond system ranged from 3.57 to 6.24 mg/L (Figure 30). The stability of DO in RAS is attributed to the system's-controlled waste management, whereby faeces and uneaten feed are removed promptly. This minimizes the oxygen demand for organic matter decomposition within the culture tanks. Moreover, DO levels can be effectively regulated, particularly after filtration, ensuring consistent oxygen availability throughout the culture period. In the earth pond system, DO levels fluctuated considerably during the observation period, generally declining as the farming cycle progressed. This reduction is primarily due to the accumulation of organic matter and the presence of plankton. At night and in the early morning, DO levels dropped further as all pond organisms engaged in respiration. Over time, the buildup of organic sediments on the pond bottom exacerbated oxygen depletion in the water column.

The pH level of the water in *Tor soro* culture is relatively more consistent in the RAS than the non-RAS system. Throughout the culture period, pH in RAS ranged from 6.89 to 7.21, whereas in the earth pond system it ranged from 6.04 to 7.65 (Figure 31). In RAS, filtration units function not only to remove organic matter but also to condition the water. Certain filter components help maintain optimal alkalinity, thereby stabilizing pH. In contrast, the non-RAS system lacks mechanisms for continuous organic matter removal and alkalinity regulation, resulting in greater pH fluctuation over time.

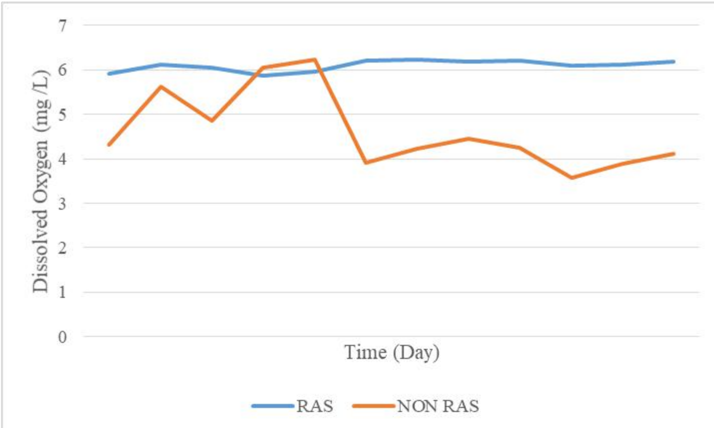

Fig 30: *Dissolved oxygen content in RAS and non-RAS during Torsoro fish farming.*

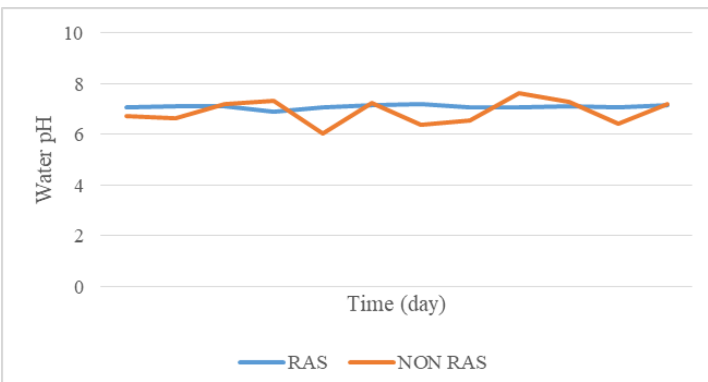

Fig 31: pH content in RAS and non-RAS during Torsoro fish farming.

In RAS system, temperatures remained stable, ranging from 26.1 to 26.8 °C, a variation of only 0.7 °C. In contrast, temperatures in the earth pond system fluctuated widely, from 25.2 to 30.2 °C, with a variation of 5.0 °C (Figure 32). Although the average temperature in the non-RAS system was higher, the large fluctuations appeared to negatively affect *Tor soro*. The significant temperature differences in non-RAS ponds are caused by the outdoor environment, where environmental factors strongly influence daily temperature fluctuations. In contrast, the RAS maintained stable temperatures due to its indoor operation, which minimizes exposure to external environmental fluctuations.

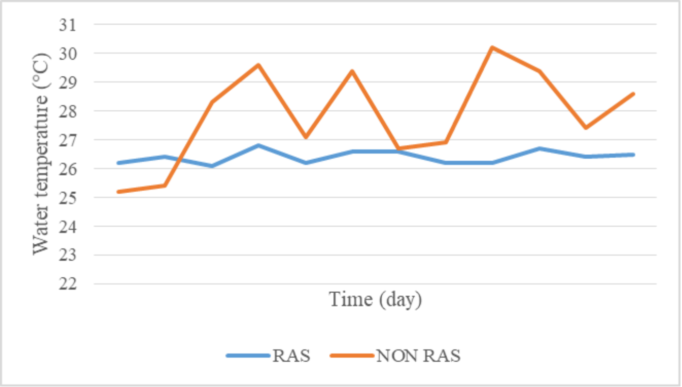

Fig 32: Water temperature content in RAS and non-RAS during Torsoro fish farming.

Ammonia levels in RAS and non-RAS were significantly different. Ammonia levels in RAS are relatively uniform, ranging from 0.011-0.021 mg/L. Ammonia in non-RAS ranged from 0.07-0.21 mg/L (Figure 33). Ammonia concentrations were consistently higher in the non-RAS system, primarily due to pond preparation practices (including the application of organic fertilizers) and the accumulation of organic matter, particularly uneaten feed settling at the pond bottom. In contrast, the RAS effectively reduced ammonia levels through its controlled filtration and waste removal processes. When operated with appropriate system design and management protocols, RAS can efficiently eliminate ammonia, thereby minimizing the risk of fish mortality from ammonia toxicity.

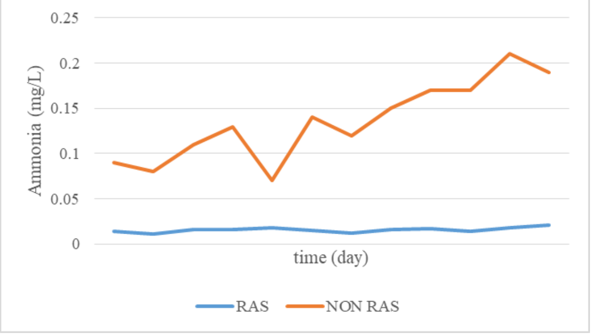

Fig 33: Ammonia content in RAS and non-RAS during Torsoro fish farming.

Alkalinity levels also differed between the RAS and non-RAS systems during *Tor soro* culture. In RAS, alkalinity remained relatively stable, ranging from 103.5 to 116.1 mg/L, whereas in the non-RAS system it fluctuated more widely, from 65.4 to 111.7 mg/L (Figure 34). Alkalinity plays a key role in buffering pH and lower alkalinity increases the likelihood of pH fluctuations. The use of specific filter media in RAS has proven effective in maintaining stable alkalinity throughout the culture period.

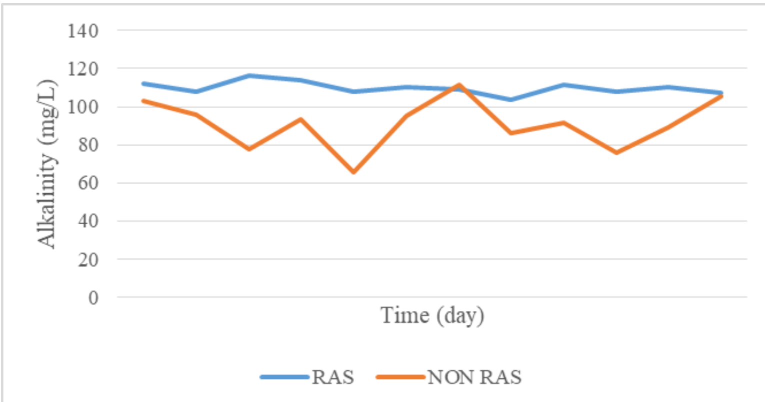

Fig 34: *Alkalinity content in RAS and non-RAS during Torsoro fish farming.*

Growth performance of Tor soro

The growth performance of *Tor soro* showed significant differences between the recirculating aquaculture system (RAS) and the non-RAS (earth pond) system (Figure 35). Fluctuations in water quality influenced feed intake and other growth-related factors. Fish reared in RAS exhibited a higher specific growth rate (SGR) and more uniform body weight compared to those in the non-RAS system. Among the measured water quality parameters, dissolved oxygen, temperature and pH appeared to have the greatest influence on growth. Dissolved oxygen, in particular, acted as a limiting factor with lower DO levels corresponded with reduced growth rates.

The use of filtration systems in RAS appears to have a positive impact on increasing the carrying capacity for *Tor soro* culture. By improving water quality, these filters support higher stocking densities, with observations indicating that RAS can sustain stocking densities 4–5 times greater than those in non-RAS (earth pond) systems (Figure 36). Filtration contributes to maintaining dissolved oxygen concentrations, thereby enabling the culture of a larger biomass. Nevertheless, further research is required to evaluate the economic feasibility and profitability of RAS implementation for *Tor soro* farming.

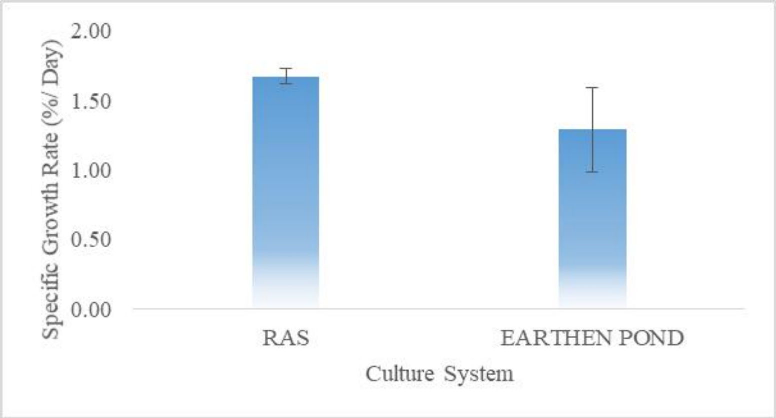

Fig 35: Specific growth rate of Torsoro fish in RAS and non-RAS over 60 days of farming.

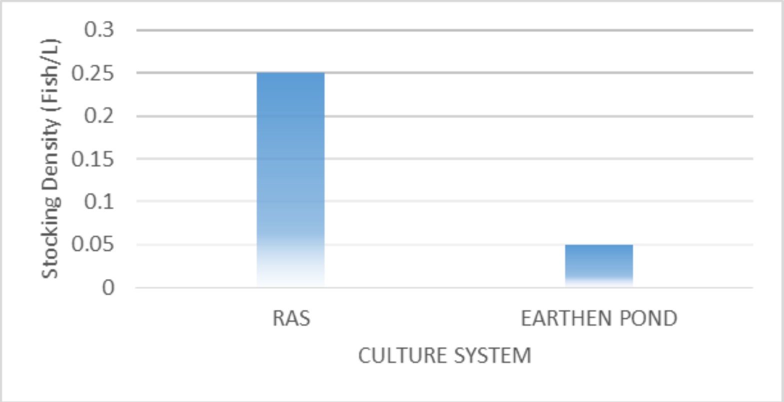

Fig 36: Stocking density of Torsoro fish in RAS and non-RAS over 60 days of farming.

Conclusion

The technology of RAS and the process of fish domestication are closely related, where applying RAS to the domestication of local freshwater fish allows for more intensive and controlled production to obtain specific characteristics and could increase economic value. The facility's equipment of RAS for *Tor soro* will be set up into several units, including recirculating system unit for larva rearing, recirculating system unit for grow-out and broodstock maintenance, quarantine/adaptation unit and additional biological filters for the fiberglass tanks. The use of a recirculating system affects the water quality in the cultivation of *Tor soro*. Dissolved oxygen, temperature, pH, ammonia and alkalinity levels in RAS system are relatively more stable than non-RAS/conventional (earth pond) systems. *Tor soro* in RAS had a higher specific growth rate compared to non-RAS. Additionally, *Tor soro* in RAS showed more uniform weight compared to those grown in non-RAS.

Reference

1. Gephart JA, Golden CD, Asche F, Belton B, Brugere C, Froehlich HE *et al*. Scenarios for Global Aquaculture and Its Role in Human Nutrition. Reviews in Fisheries Science & Aquaculture 2020; 29(1):122–38.
2. Ende S, Henjes J, Spiller M, Elshobary M, Hanelt D, Abomohra A. Recent advances in recirculating aquaculture systems and role of microalgae to close system loop. Bioresource Technology 2024; 407:131107.
3. Yustiati A, Nugroho AM, Maharani ZE, Surahman MBP andriani Y. Recirculating Aquaculture System For Ornamental Fish Production (Literature Review). JP 2024; 14(4):1774–87.
4. Martins CIM, Eding EH, Verdegem MCJ, Heinsbroek LTN, Schneider O, Blancheton JP *et al*. New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. Aquacultural Engineering 2010; 43(3):83–93.
5. Sanda Lembang M, Kuing L. Efektivitas Pemanfaatan Sistem Resirkulasi Akuakultur (Ras) Terhadap Kualitas Air Dalam Budidaya Ikan Koi (*Cyprinus rubrofuscus*). Jurnal Teknologi Perikanan dan Kelautan 2022; 12:105–12.
6. Firdausi AP, Indriastuti CE, Kusumanti I, Ramadhani DE, Tunisa RA, Maulana AZA *et al*. Efektivitas Budidaya Ikan Lele Dengan Recirculating Aquaculture System (Ras) Di Sujafish Farm, Kecamatan Cikole, Kota Sukabumi. JRKPL 2024; 11(1):1–12.
7. Setyono BDH, Junaidi M, Scabra A, Kaswadi H. Penerapan Teknologi Recirculating Aquaculture System (Ras) Untuk Perbaikan Kualitas Lingkungan Pada Budidaya Ikan Nila Di Desa Sokong Kecamatan Tanjung Kabupaten Lombok Utara. Indonesian Journal of Fisheries Community Empowerment 2021; 1:69–76.
8. Thoriq F, Wiyoto W, Iskandar A, Hermawan I. Penerapan Sistem RAS

untuk Peningkatan Kualitas Air Budidaya Ikan Patin di Pondok Pesantren Nurul Muhibbin Halong, Kalimantan Selatan. Agrokreatif: Jurnal Ilmiah Pengabdian kepada Masyarakat 2025; 11:52–9.

9. Andhika R, Dhewantara Y, Nainggolan A. Optimalisasi Kualitas Air Hujan Menggunakan Media Filter Yang Berbeda Untuk Meningkatkan Pertumbuhan Dan Sintasan Ikan Mahseer (*Tor Soro*): Optimization of Rainwater Quality Using Different Filter Media to Improve The Growth And Survival Rate Of Mahseer Fish (*Tor soro*). Jurnal Ilmiah Satya Minabahari 2024; 9:1–14.

10. Fadir R, Haser T, Febri SP, Prihadi T, Cahyanti W. Dinamika kualitas air pada pemeliharaan ikan jurung (*Tor soro*) yang dipelihara pada berbagai sistem resirkulasi. Acta Aquatica: Aquatic Sciences Journal 2022; 9:103.

11. Mulyadi, Pamukas NA, Adelina, Putra I, Sulaiman NH, Parmono T. Effectiveness of a nanofiltration membrane-based recirculation system on growth and survival of asian redtail catfish (*Hemibagrus nemurus*) under various retentate treatments. BIO Web Conf 2024;136:01008.

12. Agustiyani D, Imamuddin H, Faridah EN, Oedjijono. Pengaruh pH dan Substrat Organik terhadap Pertumbuhan dan Aktivitas Bakteri Pengoksidasi Amonia. Biodiversitas 2004; 5(2):43–7.

13. Sylvia D, Fuhrmann J, Hartel P, Zuberer D. Principles and Applications of Soil Microbiology Edited by. Upper Saddle River, New Jersey, Prentice Hall 2005;550.

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CHAPTER

The Role of Recirculating Aquaculture Systems (RAS) in Asian Sea Bass Lates calcarifer Farming: a Thorough Examination of Technology, Density, Feed and Key Challenges

Lolita Thesiana
Research Center for Fishery, National Research and Innovation Agency (BRIN), Cibinong Science Center - Gedung Biologi, Cibinong, Nanggewer Mekar, Bogor, West Java, 1692, Indonesia

Kukuh Adiyana*
Research Center for Fishery, National Research and Innovation Agency (BRIN), Cibinong Science Center - Gedung Biologi, Cibinong, Nanggewer Mekar, Bogor, West Java, 1692, Indonesia

Eddy Supriyono
Department of Aquaculture, Faculty of Fisheries and Marine Sciences, IPB University, West Java, Indonesia

I Gusti Ngurah Permana
Research Center for Fishery, National Research and Innovation Agency (BRIN), Cibinong Science Center - Gedung Biologi, Cibinong, Nanggewer Mekar, Bogor, West Java, 1692, Indonesia

Ahmad Muzaki
Research Center for Fishery, National Research and Innovation Agency (BRIN), Cibinong Science Center - Gedung Biologi, Cibinong, Nanggewer Mekar, Bogor, West Java, 1692, Indonesia

Tuti Wahyuni
Research Center for Agroindustry, National Research and Innovation Agency (BRIN), Indonesia

Corresponding Author: kuku005@brin.go.id

Abstract

Cultivation of Asian Sea Bass (*Lates calcarifer*) encounters significant obstacles such as aquatic quality, cannibalistic behavior and pathogens, which can impede the development and viability of the fish. To mitigate these challenges, the implementation of Recirculating Aquaculture Systems (RAS) presents a viable remedy. RAS utilizes mechanical and biological filtration processes that maintain water quality and reduce harmful waste such as ammonia, while also enabling better control over fish density, reducing cannibalism and regulating the fish's living space. This review covers the development of RAS technology used in *Lates calcarifer* farming, the effects of stocking density, feed management and the impact of environmental engineering on growth performance and fish survival. The findings indicate that RAS can enhance growth, survival and feed efficiency in *Lates calcarifer*, although challenges such as high operational costs and the complexity of system management remain. Overall, the implementation of RAS in Lates calcarifer farming provides a sustainable solution that improves production efficiency. It can be applied on a commercial scale with proper management in the future.

Keywords: RAS, *Lates calcarifer*, water quality, cannibalism, growth, survival.

Introduction

The cultivation of *Lates calcarifer* (Asian Sea Bass) has emerged as a central theme in the aquaculture sector owing to the elevated economic and nutritional significance of this species [1-3]. *Lates calcarifer*, commonly known as barramundi, has significant economic value due to its adaptability, rapid growth performance and high market demand [4]. This species is widely cultured in various regions, including Southeast Asia and Bangladesh, where it is considered a promising candidate for aquaculture [5]. However, farming *Lates calcarifer* faces several challenges that must be addressed to achieve optimal production success. The primary issues encountered in this farming practice include water quality, cannibalism and disease [1, 6, 7].

Substandard water quality, delineated by elevated nitrite levels and chemical contaminants, may culminate in heightened stress, diminished growth rates and lowered survival of barramundi [8]. Furthermore, this has been observed in outdoor farming using floating net cages in Belawan waters, where survival rates (SR) and average daily growth values were low due to suboptimal water conditions [9]. Cannibalism typically occurs during the early life stages of the fish, especially when high stocking densities are present in the farming system. Fish exhibiting heterogeneous dimensions will contend for nourishment and habitat, frequently culminating in cannibalism [10, 11]. Furthermore, pathogenic and nonpathogenic afflictions, exemplified by

Streptococcosis, Vibriosis and Cryptocaryonosis, represent substantial challenges. These diseases can lead to high mortality rates, particularly under stress conditions caused by poor water quality or excessive density, which affect fish health and increase their susceptibility to infections [1].

One efficacious resolution to tackle these challenges is the execution of RAS, an ecologically sustainable technology that advances enduring aquaculture methodologies [12-14]. RAS enables better water quality management through a continuous water circulation system through filtration processes, ensuring optimal water quality [15]. RAS combines mechanical, biological and chemical filtration methodologies to uphold water quality. Mechanical filters remove solid waste, while biological filters, such as nitrification trickle filters or submerged filters, convert harmful ammonia into less toxic nitrate, thereby ensuring a stable aquatic environment [16-18]. Furthermore, RAS also allows for better control in high density fish culture, by reducing competition that drives cannibalistic behavior and more effectively regulating the fish's space. The stable water quality within the system also reduces stress on the fish, enhancing their disease resistance. Therefore, the application of RAS in *Lates calcarifer* farming can address the issues of water quality, cannibalism and disease, while improving efficiency and the sustainability of fish production.

Recent studies on *Lates calcarifer* farming using RAS have focused on areas including the development of RAS technology, the impact of stocking density, feed management and the influence of environmental engineering in aquaculture. Further research is needed to identify opportunities and challenges for the future development of RAS technology, aimed at increasing fish productivity, particularly for *Lates calcarifer*.

Types of RAS Technology Used

The approach employed in RAS varies markedly depending on the system's arrangement and the objectives of the inquiry. A study [6] employed an RAS system incorporating sand, fiber and charcoal filters in cylindrical reservoirs to rear *Lates calcarifer*. This system demonstrated efficacy in augmenting fish growth performance, substantially enhancing length and weight. The fish cultivated in this framework demonstrated a mean elongation enhancement of 6.5 cm over seven weeks, accompanied by an elevated survival ratio in specimens measuring 5 cm (86%) compared to those measuring 4 cm (75%).

Another study [19] used blowers and flexible aerators to enhance dissolved oxygen concentrations in a 60 ton RAS. This study [19] focuses on developing techniques to maintain dissolved oxygen levels in two freshwater aquaculture systems for *Lates calcarifer*: RAS and the biofloc system (Floc). Oxygen enhancement was achieved using a blower connected to a flexible rubber hose aerator. This study aimed to assess the efficacy of oxygenation utilizing three distinct varieties of aerators: a 400 W air propulsion apparatus equipped with flexible rubber tubing, a singular 250 W ejector aerator assembly and two 250 W ejector aerator assemblies (culminating in a total of 500 W). The assessment of oxygenation's effectiveness involved looking at key factors, including the oxygen transfer coefficient (kLa), the oxygen transfer rate (OTR) and the aeration efficiency (AE).

The results of the first experiment demonstrated that the aerator with flexible rubber tubing (400 W) exhibited superior oxygenation efficiency compared to the ejector aerators, reaching oxygen saturation (~7.40 mg/L) in approximately 0.58 hours, significantly faster than the single set ejector aerator (7.0 hours) and the double set ejector aerator (5.5 hours). The kLa value of the flexible hose aerator (0.0609 ± 0.0010 /min) was also significantly higher than that of the ejector aerators (0.0321 ± 0.0017/min for one set and 0.0519 ± 0.0017/ min for two sets). This type of aerator was deemed most suitable for fish culture in RAS due to its ability to generate fine bubbles, increasing the specific contact area and resulting in the highest oxygen transfer rate (135 g O_2/h) and aeration efficiency (338 g O_2/kW/h).

In addition to comparing aerator efficiency, the study evaluated the performance of RAS and Floc systems, the accumulation of unpleasant smell compounds (geosmin and 2-methylisoborneol/MIB) and economic feasibility. The results indicated that freshwater barramundi cultured in the RAS had higher yields and growth rates than those in the biofloc pond system. Fish survival rates were also higher in RAS (89.3 ± 5.6% in RAS1, 87.4 ± 6.9% in RAS2) than in Floc (56.5 ± 5.0% in Floc1, 52.7 ± 8.6% in Floc2).

This advantage was attributed mainly to better controlled water quality, notably significantly lower total ammonia nitrogen (TAN) levels (0.13 ± 0.04 ppm in RAS1, 0.17 ± 0.02 ppm in RAS2) compared to Floc systems (0.42 ± 0.10 ppm in Floc1, 0.45 ± 0.22 ppm in Floc2), due to the effectiveness of the Moving Bed Bioreactor (MBBR) ammonia treatment system, which was designed to support up to 24.2 kg/day of feed input with a TAN removal efficiency of 607 g/m^3/day. Moreover, the average water temperature in the plastic-covered RAS (29.5 ± 0.8 °C in RAS1, 29.3 ± 0.1 °C in RAS2) was approximately 2 °C higher than in the Floc systems (27.5 ± 0.3 °C in Floc1, 27.2 ± 0.2 °C in Floc2), which favors barramundi growth, as the optimal temperature range is 28–31 °C.

The study also observed variations in dissolved oxygen after alimentary intake, disclosing a pronounced elevation in oxygen consumption following feeding. A feeding frequency trial showed that feeding six times daily resulted in higher minimum dissolved oxygen levels (3.6–6.4 ppm) than feeding twice daily (2.3–6.5 ppm), where oxygen dropped below 2.5 ppm after meals, considered a critical threshold. Accumulation of biological sludge and off-flavor compounds (geosmin and MIB) was higher in the Floc system than in RAS. However, the overall concentrations in both systems were low and did not adversely affect fish flesh quality. Overall, the investigation [19] determined that RAS, particularly when employing adaptable rubber tubing aerators and with prospective enhancements in feeding frequency, is more appropriate and lucrative for extensive (60 ton) freshwater barramundi cultivation.

Another study evaluated the application of RAS incorporating mechanical and biological filtration, thermal regulation, aeration and optimal water quality management [20]. In this study, fish cultivated in RAS exhibited enhanced growth, with statistically significant augmentations in both length and mass when juxtaposed with those nurtured in static water systems (SWS). RAS was shown to enhance feed efficiency and reduce cannibalism in *Lates calcarifer*. A study [21] also noted that RAS can support high stocking densities of up to 4500 fish/m³. In this study, RAS was equipped with several essential components such as mechanical filters, biofilters using bioball and bioblock media and a protein skimmer to maintain water quality. Water was circulated using automatic pumps and to ensure stable conditions, the system was equipped with water heaters and a UV sterilization system. Overall, the RAS technology used in this study proved effective for *Lates calcarifer* fry rearing at densities of up to 3000 fish/m³, achieving optimal growth and reasonable water quality control. However, challenges remain related to increasing the biofilter capacity to support higher densities.

Recent developments in RAS technology for larger scale *Lates calcarifer* fry rearing have also been undertaken at the Center for Marine Aquaculture Research and Fisheries Extension, Gondol Bali, Indonesia. This RAS has a water capacity for farming of 80 tons, with stocking densities of 4000 and 6000 fish/tank (Figure 37). Technological advancements include integrating mechanical filters, biofilters, protein skimmers and oxygenation using Micronano Bubbles (MNBs). The research results show that the RAS technology maintained good water quality throughout farming. High stocking density impacted survival rates but did not affect fish growth. The optimal survival rate of 73.19% was attained at a stocking density of 4000 specimens/tank, with a mean harvest mass of 33 grams.

Fig 37: High density Lates calcarifer rearing with RAS technology in Bali, Indonesia

Effect of Fish Stocking Density

Fish stocking density is a crucial factor significantly impacting RAS system growth performance and survival rates. It was ascertained that reduced stocking densities (0.5 individuals/L) in white tanks culminated in enhanced growth and elevated survival rates [10]. However, cannibalism rates were higher in white tanks than black tanks, despite the higher stocking density (1.5 individuals/L), resulting in lower growth per individual. Another study [22] showed that higher stocking densities (350 fish/m^3) in RAS systems increased the expression of stress genes in fish, negatively affecting growth and health. In contrast, a stocking density of 70 fish/m^3 resulted in enhanced growth, alongside improved digestive enzyme activity and body composition.

In the study [21], three distinct stocking densities were evaluated for the rearing of *Lates calcarifer* fry: 3000 fish/m^3 (1.17 kg/m^3), 4500 fish/m^3 (1.75 kg/m^3) and a control group with 1500 fish/m^3 (0.62 kg/m^3). The findings suggested that the variations in density did not significantly influence fish length and weight increment. Fish at the 3000 fish/m^3 density reached an average length of 8.47 cm and a weight of 10.26 g, while fish at 4500 fish/m^3

reached a length of 8.29 cm and a weight of 9.35 g and the control group at 1,500 fish/m³ reached a length of 8.38 cm and a weight of 10.56 g. While the growth was relatively similar across all treatments, survival rates showed significant differences. The highest survival rate was realized in the control cohort (82.62%), succeeded by 3000 fish/m³ (48.80%) and 4500 fish/m³ (42.7%), indicating a decline in survival as stocking density escalated. Moreover, this was correlated with heightened cannibalism, which was most pronounced at 4500 fish/m³ (39.91%), followed by 3000 fish/m³ (33.18%), whereas the control cohort recorded merely 11.00% cannibalism. Overall, while density did not significantly impact growth, increased stocking density was directly associated with a reduction in survival and an elevation in cannibalism among the fish.

The investigation [22] assessed the impacts of differing stocking densities on growth efficacy, digestive enzyme functionality, body composition and gene expression in *Lates calcarifer* cultivated in RAS. Although high stocking density can generally increase yield per unit area, this study demonstrated that increasing stocking density (from 70 to 350 fish/m³) significantly reduced the growth performance of barramundi in RAS. Specifically, final weight gain, specific growth rate (SGR) and survival rate decreased with increasing stocking density. The lowest density (70 fish/m³) recorded a significantly higher survival rate (95.00 ± 1.25%) than higher densities. Conversely, feed conversion ratio (FCR) and mortality increased at higher densities, indicating poorer feed utilization efficiency.

Furthermore, this study also discovered that the functions of digestive enzymes, encompassing protease, amylase, lipase and cellulase, markedly diminished in fish cultivated at elevated stocking densities [22]. This decrease in digestive enzyme functionality implies a diminished capacity of the fish to metabolize, assimilate and exploit nutrients from the feed. The body composition of the fish was also affected, with reduced crude protein and lipid contents and increased ash content at higher densities. Moreover, this is presumably due to fish allocating most of their metabolic energy to cope with crowding stress rather than protein and lipid deposition.

At the molecular stratum, gene expression assessment elucidated that augmenting stocking density precipitated the downregulation of growth-associated genes (GH/IGF-1) and the upregulation of the myostatin (MSTN) gene within the hepatic tissue. GH/IGF-1 performs a pivotal function in growth regulation, whereas MSTN is a negative modulator of muscular development. These changes in gene expression align with the observed decline in growth performance at higher densities, indicating that crowding stress impacts growth through the modulation of hepatic gene expression.

Overall, this sixty day study concluded that increasing stocking density in RAS induces chronic stress, negatively affecting feed intake, metabolism, nutrient absorption and growth performance in barramundi. Therefore, the study recommends that the culture of *Lates calcarifer* in RAS should be carried out at a maximum stocking density of 70 fish/m³ to enhance growth performance and metabolic and molecular activity.

Feed Management

Feed management is a critical factor influencing Lates calcarifer farming production efficiency. The diet's augmentation with 1% calcium and 1% phosphorus can improve fish's growth and survival rate [23]. This supplementation also improved hematological and biochemical parameters, indicating that optimal feed composition can improve fish health and productivity in RAS systems. Furthermore, the ideal alimentary frequency is thrice daily, which culminated in the most favourable growth and enhanced feed conversion efficiency [24]. Proper feeding can influence the fish's body condition, with better hepatosomatic and viscerosomatic indices observed in groups fed three to four times daily. However, lower feeding frequencies increased lipid content in the fish.

An extensive comparative study and evaluative investigation regarding the efficacy of nutrition augmented with a mineral premix in the freshwater RAS cultivation of barramundi (*Lates calcarifer*) has been done and this research was grounded in the understanding that macro- and micromineral nutrition are critical to fish diets to ensure healthy growth and maintain physiological integrity. Macrominerals, including calcium, phosphorus, magnesium, sodium, chloride, potassium and sulfur and microminerals like manganese and selenium, are considered vital, with supplementary trace minerals necessary in tiny quantities [25].

To empirically investigate this, a 60 day culture trial was conducted using 500 liter tanks within a freshwater RAS, stocked with barramundi fingerlings sourced from Cochin, Karnataka, India. The empirical framework encompassed ten distinct alimentary formulations augmented with diverse concentrations of mineral premix (oscillating from 0.1% to 1.0%), in conjunction with two control regimens one devoid of supplementation and the other with a benchmark level predicated on antecedent investigations. The specific composition of the mineral premix was detailed, comprising magnesium chloride (7.51%), sodium chloride (9.86%), potassium hydroxide (12.50%), ferrous sulfate heptahydrate (8.27%), copper sulfate pentahydrate (0.98%), zinc sulfate heptahydrate (3.35%), manganese sulfate monohydrate (0.48%) and sodium selenite (0.04%). The specific composition of the mineral premix was detailed, comprising magnesium chloride (7.51%), sodium chloride (9.86%), potassium hydroxide (12.50%), ferrous sulfate heptahydrate (8.27%), copper sulfate pentahydrate (0.98%), zinc sulfate heptahydrate (3.35%), manganese sulfate monohydrate (0.48%) and sodium selenite (0.04%).

A comprehensive set of parameters was measured to evaluate feed performance and the physiological status of the fish. These included growth performance indicators (such as specific growth rate and feed conversion ratio), whole body proximate composition (protein, lipid, moisture, ash, fiber, nitrogen free extract), blood biochemical parameters (lipase, amylase, cholesterol, triglycerides, uric acid, urea, albumin, globulin, A/G ratio, total protein, C-reactive protein, alkaline phosphatase), hematological parameters (white and red blood cell counts, hemoglobin, hematocrit, mean corpuscular volume, mean corpuscular hemoglobin, mean corpuscular hemoglobin concentration, platelet count and platelet distribution width) and serum and glutathione-related antioxidant activities (including superoxide dismutase (SOD), nitro blue tetrazolium (NBT), peroxidase and alkaline phosphatase). Water quality parameters in the RAS, such as temperature, dissolved oxygen (DO), pH, salinity, hardness, ammonia, nitrite and nitrate, were also regularly monitored to ensure stable and optimal environmental conditions throughout the study.

Statistical analysis divulged that these variables were significantly affected by the extent of mineral enrichment. Based on a holistic evaluation of growth, biochemical and hematological parameters, the study concluded that 0.8% supplementation of macro and micromineral premix in the feed was the most optimal and essential level for supporting the growth and health of *Lates calcarifer* in freshwater RAS. The findings strongly confirmed that mineral supplementation is necessary and significantly impacts barramundi's physiological and growth aspects under freshwater culture conditions. These findings are congruent with antecedent investigations in alternative fish species, which have similarly substantiated the significance of particular mineral augmentations such as magnesium, sodium, zinc and selenium for maximal growth and fish health. This study makes a substantial contribution by discerning the ideal mineral supplementation threshold for barramundi cultivated in freshwater RAS, furnishing essential insights for advancing efficacious feed formulations [25].

Impact of Tank Color on Asian Sea Bass Productivity

Environmental engineering constitutes one of the pivotal elements that can be employed to augment the productivity of *Lates calcarifer* in RAS. One ecological variable that can be altered for enhanced outcomes is the pigmentation of the tank, which has been demonstrated to considerably affect growth performance and feed efficiency in fish species.

A study [26] explored the ramifications of various tank background colors (white, red, black and blue) on growth metrics, body composition, digestive enzyme functionality, hematological and blood biochemical variables, in addition to the expression of stress- and growth-associated genes in juvenile barramundi (*Lates calcarifer*). 180 fish with an initial average weight of 160.90 ± 6.0 g were distributed into twelve cylindrical polyethylene tanks (250 L volume), each lined with colored sheets representing the four background treatments. The trial lasted six weeks, during which the fish were fed a commercial diet to satiation twice daily.

The results demonstrated that tank background color positively influenced juvenile barramundi growth performance and feed utilization. Specific Growth Rate (SGR), Protein Efficiency Ratio (PER) and Weight Gain (WG) were markedly elevated in fish specimens cultivated in red background tanks, followed by white and black tanks, with the lowest values recorded in the blue tanks. No substantial variances were detected among the treatments concerning initial and final body weight, Daily Feed Intake (DFI), Condition Factor (CF), Feed Conversion Ratio (FCR) and survival rate, which consistently remained at 100% across all treatments.

In terms of physiological and stress related parameters, serum cortisol levels were significantly lower in fish held in red tanks (12.9 ± 0.1 ng/ml), indicating reduced stress levels compared to black (15.2 ± 0.3 ng/ml), white (14.5 ± 0.55 ng/ml) and blue tanks (14 ± 0.5 ng/ml). Blood glucose and lactate levels were the highest in fish from white tanks, followed by red, black and blue. In contrast, albumin concentrations were significantly elevated in blue, black and red tanks relative to white tanks. The total protein content was higher in red and blue tanks compared to black and white backgrounds. No notable variations were found among the interventions concerning hematological metrics such as RBC, WBC, HCT, Hb and LYM.

The activities of digestive enzymes, including protease, lipase and amylase, exhibited no notable variations across the treatment groups. The expression of the growth-associated gene (IGF-I) and the immune associated gene (Lysozyme) was markedly diminished in fish cultivated in white tanks compared to those in blue tanks. In contrast, no significant distinctions were noted between black and red tanks and other interventions. Based on superior growth performance and relatively lower stress levels (as indicated by lower cortisol concentrations), from this study, it can be concluded that red is the most suitable background color for rearing juvenile barramundi, followed by white, in comparison to other colors [26].

In contrast, a study [27] investigated the influence of tank backdrop hue (transparent, white, black, red, green and blue) on culture efficacy, feed efficiency, digestive enzyme functionality, flesh quality, carcass constitution and hematological indicators in barramundi (*Lates calcarifer*). This study distributed barramundi with an initial mean body weight of 16.17 ± 0.02 g into eighteen glass aquaria. The outer and bottom surfaces of the tanks were covered with grooved polypropylene boards of different colors, representing six color treatments with three replicates each and each tank stocked with 15 fish. The fish were fed commercial floating pellets *ad libitum* twice daily for 10 weeks.

The results demonstrated that tank background color significantly influenced growth performance and feed utilization. Positive growth and feed utilization outcomes were observed in fish reared under transparent, white, black or green backgrounds, showing superior growth rates and feed efficiency compared to those maintained under red and blue backgrounds. Specifically, blue backgrounds had an adverse effect on final body weight (FBW), weight gain (WG) and final body length (FBL) relative to the transparent control treatment. Improved feed utilization, indicated by lower Feed Conversion Ratios (FCR) and higher Protein Efficiency Ratios (PER), was recorded in fish under transparent, white, black and green backgrounds.

A potential explanation for these findings is the contrast between the feed color (dark brown) and the tank background, which may enhance feed visibility and intake, particularly in transparent and white backgrounds. In the case of black backgrounds, although visual contrast might be poor, no adverse effects were observed, possibly due to the feeding behavior of juvenile barramundi, which approach pellets from below and capture them via suction. Thus, the contrast between the pellet and the ceiling (rather than the tank bottom) may be more critical.

Furthermore, background color may influence neural and hormonal responses, including the secretion of stress hormones. Black backgrounds are known to possibly elevate α-Melanocyte Stimulating Hormone (α-MSH). In contrast, white ones might enhance the melanin concentrating hormone (MCH), which links to physical growth and energy conservation. Green backgrounds also had a positive effect, potentially due to marine fish's sensitivity to short wavelengths and complex interactions involving visual pigments, neural responses and hormonal regulation. Red and blue backgrounds were suboptimal, showing inferior feed utilization. Although some background colors (white, black, red, green) resulted in lower hepatosomatic index (HSI) values, potentially indicating stress, this stress level may not have been sufficient to impair growth. It could even be beneficial to a certain extent, especially considering that no mortality occurred and preferred treatments yielded superior performance.

Regarding digestive enzyme functionality, tank background hue substantially influenced the performance of pepsin, trypsin, chymotrypsin, α-amylase and lipase. Intriguingly, while the black backdrop yielded comparatively diminished digestive enzyme efficacy, the trypsin-to-chymotrypsin ratio (T/C ratio) was maximized in both black and white backdrops, corresponding with enhanced growth and feed efficiency in these groups. The T/C ratio is a reliable indicator of growth and feed efficiency in several fish species.

The highest RNA concentrations and RNA/protein ratios were observed in fish from blue backgrounds regarding flesh quality. In contrast, higher protein concentrations were recorded in fish reared in black, white and green backgrounds. Low RNA concentration and RNA/protein ratio, combined with increased flesh protein content, suggest a more advanced growth phase in fish reared in black backgrounds, followed by green and white. No significant differences appeared in myosin and actin concentrations, reflecting standard functionality of the muscles. Carcass composition (moisture, crude protein) was generally unaffected, except for higher crude lipid content in fish from transparent, white and green backgrounds and lower ash content in those from red backgrounds. Hematological parameters revealed significant differences in BUN and ALP. Elevated BUN levels in some treatments (white, black, red, blue) may be associated with dietary protein utilization or digestive enzyme activity, rather than kidney damage, as ALP levels remained within the normal range, indicating no hepatotoxic or nephrotoxic effects.

Based on growth performance, feed utilization, digestive enzyme activity, flesh quality, carcass composition and hematological parameters in this study [27], it can be concluded that black was the most suitable background hue for rearing *Lates calcarifer*, followed by white and green. Thus, environmental engineering through carefully selecting tank color can be an effective strategy to improve the productivity of *Lates calcarifer* in RAS, resulting in better growth, feed efficiency and meat quality outcomes.

Achievements and Challenges in the Use of RAS

Overall, existing research indicates that RAS can enhance efficiency in *Lates calcarifer* farming by improving water quality, density management and feed administration. Nevertheless, the principal obstacles that persist encompass elevated operational expenditures and the intricacy of system management. According to a study [6], while RAS effectively produces fish with reasonable growth rates and high survival, carefully managing fish density and water quality is still essential to maximize the system's potential. A study [19] indicated that RAS can enhance production efficacy, but the expenses related to aeration and nutrition remain a challenge for the economic feasibility of the setup. Therefore, although RAS offers many benefits, efficient management and rigorous monitoring of water quality and fish health are crucial to ensure the system's success in *Lates calcarifer* farming.

Conclusion

The utilization of RAS in *Lates calcarifer* aquaculture has demonstrated markedly favorable outcomes in augmenting growth, survivability and production efficacy. With proper management of fish density, feeding practices and water quality, RAS can serve as a sustainable solution for more efficient and environmentally friendly fish production. Although challenges related to cost and energy management remain, research indicates that the long-term benefits of using RAS far outweigh these challenges, making it a highly recommended method for *Lates calcarifer* farming.

References

1. Chudasama RV. A Short Review of Asian Seabass (*Lates calcarifer*) Cultivation. Indian Journal of Pure & Applied Biosciences 2023; 11(3): 17–35. https://doi.org/10.18782/2582-2845.8980.

2. Yanti RZ, Muchlisin ZA, Muhammadar AA, Fadli N. Application of pumpkin flour to the diet of Barramundi *Lates calcarifer* fingerling. DEPIK 2022; 11(2): 176–181. https://doi.org/10.13170/depik.11.2.26859

3. Faizah F, Kurniawati AD, Khairunnisa A, Agustini NPS. Penerapan Cold Chain Storage Pada Pembekuan Filet Kakap Putih (*Lates calcarifer*). Journal of Technology and Food Processing (JTFP) 2023; 3(02): 42–47. https://doi.org/10.46772/jtfp.v3i02.1280.

4. Islam NMA, Bosu NA, Hasan NMM, Yasmin NF, Khan NBS, Akhter NM *et al*. Culture technique of seabass, *Lates calcarifer* in Asia: A review. International Journal of Science and Technology Research Archive 2023; 4(1): 006–017. https://doi.org/10.53771/ijstra.2023.4.1.0174.

5. Farhaduzzaman AM, Khan MS, Osman MH, Shovon MNH, Azam M, Makhdum N. Progress of seabass, *Lates calcarifer* (Bloch, 1970) culture in Bangladesh: Field-level updates from the Bhola and Satkhira Districts. International Journal of Agricultural Research Innovation and Technology 2023; 12(2): 117–125. https://doi.org/10.3329/ijarit.v12i2.64097.

6. Sahusilawane HA, Metungun J, Fitrinawati H, Kilmanun JE. Growth performance of white seabass (*Lates calcarifer*) cultivated using recirculation aquaculture system (RAS). BIOEDUPAT Pattimura Journal of Biology and Learning 2024; 4(2): 214–219. https://doi.org/10.30598/bioedupat.v4.i2.pp214-219.

7. Abduh NAM, Makus NMK, Djudin NR, Anwar NNA, Abdullah NT. Vibriosis in Asian Seabass *Lates calcarifer* (Bloch, 1790). Jurnal Ilmiah Platax 2024; 12(2): 281–297. https://doi.org/10.35800/jip.v12i2.58876.

8. Hu J, Allais L, Yang R, Liu Y, Zhou S, Qin J *et al*. Physical Responses of *Lates calcarifer* to Acute Nitrite Stress. Israeli Journal of Aquaculture – Bamidgeh 2019; 71. https://doi.org/10.46989/001c.20993.

9. Lubis VIS, Nirmala K, Supriyono E, Hastuti YP. Monitoring the water quality of Belawan Sea for rearing asian seabass *Lates calcarifer* in a floating net cage system. Jurnal Akuakultur Indonesia 2024; 23(2): 269–280. https://doi.org/10.19027/jai.23.2.269-280.

10. Khan MSK, Salin KR, Yakupitiyage A, Tsusaka TW, Shrestha S, Siddique MAM. Effect of stocking density and tank colour on nursery growth performance, cannibalism and survival of the Asian seabass *Lates*

calcarifer (Bloch, 1790) in a recirculating aquaculture system. Aquaculture Research 2022; 53(6): 2472–2483. https://doi.org/10.1111/are.15765.

11. Khan MSK, Salin KR, Yakupitiyage A, Tsusaka TW, Nguyen LT, Siddique MAM. L-Tryptophan Mitigates Cannibalism and Improves Growth of Asian seabass, *Lates calcarifer* Reared in a RAS System. Aquaculture Journal 2023; 3(3): 168–180. https://doi.org/10.3390/aquacj3030014.
12. Supriyono E, Adiyana K, Thesiana L. A Study of Environmentally Friendly Recirculating Aquaculture System on Lobster *Panulirus homarus* Nursery. Polish Journal of Environmental Studies 2023; 32(5): 4805–4811. https://doi.org/10.15244/pjoes/166596.
13. Supriyono E, Thesiana L, Adiyana K. Biochemical response and production performance of spiny lobster *Panulirus homarus* seed reared with different shelter materials. Indian Journal of Fisheries 2022; 69(3). https://doi.org/10.21077/ijf.2022.69.3.118515-08.
14. Supriyono E, Rasul N, Budiardi T, Hastuti YP, Adiyana K, Thesiana L. A study on the effect of different colours of culture tanks in nursery, on the production performance, biochemical composition of flesh and physiological responses of whiteleg shrimp (*Litopenaeus vannamei*). Aquaculture Research 2021; 52(9): 4086–4093. https://doi.org/10.1111/are.15246.
15. Lal J, Vaishnav A, Deb S, Kashyap S, Debbarma P, Devati N *et al*. Re-Circulatory Aquaculture systems: a pathway to sustainable fish farming. Archives of Current Research International 2024; 24(5): 799–810. https://doi.org/10.9734/acri/2024/v24i5756.
16. Beg MM, Roy SM, Kar A, Mukherjee CK, Bhagat SK, Tanveer M. Study on recirculating aquaculture system (RAS) in organic fish production. IOP Conference Series Earth and Environmental Science 2024; 1391(1): 012013. https://doi.org/10.1088/1755-1315/1391/1/012013.
17. Thesiana L, Adiyana K. Design of submerged fixed bed filter for high density shrimp culture in recirculating aquaculture system. IOP Conference Series Earth and Environmental Science 2021; 695(1): 012025. https://doi.org/10.1088/1755-1315/695/1/012025.
18. Thesiana L, Adiyana K, Zulkarnain R, Moersidik SS, Gusniani I,

Supriyono E. Ecofriendly land-based spiny lobster (*Panulirus sp.*) rearing with biofilter application in recirculating aquaculture system. IOP Conference Series Earth and Environmental Science 2020; 404(1): 012082. https://doi.org/10.1088/1755-1315/404/1/012082.

19. Whangchai N, Klahan R, Balakrishnan D, Unpaprom Y, Ramaraj R, Pimpimol T. Development of aeration devices and feeding frequencies for oxygen concentration improvement in 60-tones freshwater recirculating aquaculture and biofloc ponds of Asian seabass (*Lates calcarifer*) rearing. Chemosphere 2022; 307: 135761. https://doi.org/10.1016/j.chemosphere.2022.135761
20. Khan MSK, Salin KR, Yakupitiyage A, Siddique MAM. Effect of stocking densities on the growth performance, cannibalism and survival of Asian seabass *Lates calcarifer* (Bloch, 1790) fry in different nursery rearing system. Aquaculture Research 2021; 52(11), 5332-5339. https://doi.org/10.1111/are.15403.
21. Permana GN, Pujiastuti Z, Fakhrudin F, Muzaki A, Mahardika K, Adiyana K. Aplikasi Sistem Resirkulasi Pada Pendederan Ikan Kakap Putih, *Lates calcarifer* Kepadatan Tinggi. Jurnal Riset Akuakultur 2019; 14(3): 173. https://doi.org/10.15578/jra.14.3.2019.173-182.
22. Ezhilmathi S, Ahilan B, Uma A, Felix N, Cheryl A, Lingam RSS. Effect of stocking density on growth performance, digestive enzyme activity, body composition and gene expression of Asian seabass reared in recirculating aquaculture system. Aquaculture Research 2022; 53(5): 1963-1972. https://doi.org/10.1111/are.15725.
23. Moses TS, Ahilan B, Chidambaram P, Felix N, Jayakumar N. Optimizing the Supplementation of Calcium and Phosphorus in the Diets of Asian Seabass (*Lates calcarifer*) in Freshwater based Recirculating Aquaculture System. Indian Journal of Animal Research 2024. https://doi.org/10.18805/ijar.b-5409.
24. Hassan HU, Ali QM, Khan W, Masood Z, Abdel-Aziz MA, Shah MIA *et al*. Effect of feeding frequency as a rearing system on biological performance, survival, body chemical composition and economic efficiency of Asian seabass *Lates calcarifer* (Bloch, 1790) reared under controlled environmental conditions. Saudi Journal of Biological Sciences 2021; 28(12): 7360-7366. https://doi.org/10.1016/j.sjbs.2021.08.031

25. Moses TS, Ahilan B, Chidambaram P, Felix N, Jayakumar N. Comparison and Evaluation of the Performance of the Mineral Mix Supplemented Diet for Asian Seabass (*Lates calcarifer*) Culture in Fresh Water-based Recirculating Aquaculture System. Indian Journal of Animal Research 2024. https://doi.org/10.18805/ijar.b-5435.

26. Morshedi V, Pradhoshini KP, Tangestani N, Ghasemi A, Sotoudeh E, Gamoori R *et al*. Effects of rearing tank colour on growth indices, blood chemistry, digestive enzymes, expression of stress and growth-related genes of Asian sea bass juvenile (*Lates calcarifer)*. Aquaculture Research 2022; 53(10): 3780-3787. https://doi.org/10.1111/are.15884.

27. Santisathitkul N, Thongprajukaew K, Saekhow S, Sandos P, Buntomnimit S, Kanghae H. Optimal background colour for rearing Asian seabass (*Lates calcarifer*). Aquaculture Research 2020; 51(4): 1743-1752. https://doi.org/10.1111/are.14521.

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11
CHAPTER

Effectiveness of RAS on Grouper Growth Performance, Feed Efficiency and Fish Health

Suhardi Atmoko Budi Susilo
Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia

Dendy Mahabror*
Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia

Riza Zulkarnain
Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia

Asmanik
Research Center for Mariculture, National Research and Innovation Agency (BRIN), Indonesia

Indra Pratama
Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia

Sri Suryo Sukoraharjo
Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia

Corresponding Author: dendymahabror@gmail.com

Abstract

Grouper fish farming is a high-value aquaculture commodity, but conventional systems face significant constraints such as poor water quality, disease and low feed efficiency. Recirculating Aquaculture System (RAS) technology offers an innovative solution through closed-water circulation and layered filtration, allowing complete control of aquaculture environmental parameters. This chapter is a literature review that analyzes the effectiveness of RAS in improving grouper growth, feed conversion and health, as well as its contribution to environmental and economic sustainability. Data from various international journals show that RAS increases feed Conversion Ratio (FCR up to 1.04), improves fish biochemical profiles and reduces mortality due to disease. In addition, RAS supports circular economy practices and water savings of up to 90%. This article confirms that RAS is a strategic approach for sustainable grouper production in the future.

Keywords: Recirculating Aquaculture System (RAS), Grouper, FCR, Sustainable Aquaculture, Fish Health.

Introduction

Farmed grouper has a high economic value and is a leading export commodity in many Asian countries, such as Indonesia, Malaysia and China. Growing market demand has encouraged production intensification, but conventional aquaculture systems face various problems, including declining water quality, the emergence of diseases and high feed conversion ratios that impact production efficiency. Conventional grouper culture systems (ponds) have a higher feed conversion ratio (FCR) (1.21) than RAS (0.88), indicating feed inefficiency in open systems [1]. Conventional systems are generally still open and highly dependent on the quality of the external environment, which makes them vulnerable to fluctuations in environmental parameters and external pollution.

The Recirculating Aquaculture System (RAS) was developed to overcome these challenges and provide an innovative alternative to fish farming, including grouper farming. RAS is a closed system capable of circulating aquaculture water through mechanical, biological and chemical filtration stages, enabling repeated water use with maintained quality. In the context of grouper aquaculture, RAS allows spawning, hatching and rearing to be controlled throughout the year. Several studies have shown that RAS improves growth and feed efficiency and helps reduce diseases that often affect grouper seeds and juveniles [2].

From an economic and environmental perspective, using this technology is also in line with the principle of sustainability, as RAS reduces water consumption, waste and the risk of pollution to natural waters. Genetic development, application of technologies such as nanobubbles and bioeconomic approaches also strengthen the potential of RAS as a superior production system for grouper [3, 4]. Comparative studies between RAS and conventional pond systems in grouper aquaculture show that despite RAS's higher initial investment and operational costs, the system produces better feed efficiency, faster growth and lower mortality rates. In the long run, RAS is considered to increase profit margins through production efficiency, reduce disease risk and support sustainable aquaculture, as waste and water use can be minimized [1]. Therefore, this article aims to review recent studies on the growth, efficiency, genetics, fish health and economic implications of RAS in grouper aquaculture.

RAS Technology Developments and Benefits for Grouper Farming

The application of Recirculating Aquaculture Systems (RAS) for grouper offers several advantages over traditional pond culture methods, which are often prone to disease, low productivity and environmental pollution. Here are the developments, key benefits and considerations for using RAS in grouper farming.

The Development of Modern Technology in Recirculating Aquaculture Systems

The following are the components of the Recirculating Aquaculture System (RAS) system in Figure 7 for grouper fish farming, complete with a technical explanation of each component:

a. Culture Tank

The culture tank is the main container for rearing groupers in a controlled environment. The water from this pond contains feed residue and fish feces.

b. Mechanical Filter

A mechanical filter functions to remove solid particles, such as feces and uneaten feed, before the water enters the next unit.

c. Protein Skimmer

Protein skimmers remove dissolved organic compounds and fine waste materials by forming air bubbles and bringing impurities to the surface for removal.

d. Biofilter

The biofilter houses nitrifying bacteria that convert toxic ammonia into nitrites and then nitrates, which are less harmful to fish.

e. Degassing Unit

The degassing unit removes excess dissolved gases such as CO_2 and H_2S, maintaining gas balance so that fish metabolism remains optimal.

f. Oxygen Generator

Oxygen generators provide dissolved oxygen enrichment into the water through direct injection to support fish growth and metabolism.

g. UV Lamp in Sump Tank

It uses ultraviolet light to sterilize water, killing pathogens and microorganisms that could cause disease.

h. Pump

The pump continuously circulates water through all system components, ensuring efficient circulation and filtration.

The Recirculating Aquaculture System (RAS) is a closed aquaculture technology approach that allows continuous and efficient maintenance of water quality, especially suitable for grouper farming, which is sensitive to environmental fluctuations. The process starts from the culture tank, which is the principal place where groupers are raised. In this tank, the fish produce organic waste such as feces, feed residue and metabolic compounds such as ammonia. Water from the culture tank is continuously fed to the filtration system through a pump to filter and recondition the water quality before reuse.

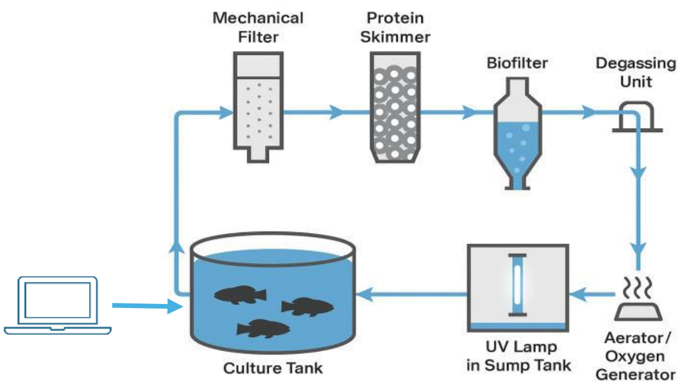

Fig 38: Recirculating Aquaculture System (RAS) for Grouper Farming

The first step in water treatment is the mechanical filter, which filters out coarse particles and suspended solids from fish waste. Next, the water flows to the protein skimmer. This device eliminates dissolved organic compounds by forming microbubbles that bring impurities to the surface for removal, maintaining water clarity and lowering the workload of the biofilter. Afterward, the water is directed to the biofilter, a vital component in the biological nitrification process. Here, nitrifying bacteria convert ammonia (NH_3) into nitrite (NO_2^-) and then into nitrate (NO_3^-), which is relatively safer for fish in limited concentrations.

Water that has undergone a biological process then enters the degassing unit. This unit serves to remove excess dissolved gases such as carbon dioxide

(CO_2), nitrogen (N_2) and hydrogen sulfide (H_2S), which, if not controlled, can cause respiratory stress or even fish death. After degassing, the water enters a sump tank equipped with a UV lamp to sterilize the water from pathogens and an oxygen generator or aeration system to increase dissolved oxygen (DO) levels. This process is important to meet the high metabolic needs of fish, especially in high stocking density systems.

The clean and oxygenated water is then pumped back into the culture tank, forming a continuous and efficient water circulation cycle. To optimize system management, the monitoring and automation panel has real-time sensors that measure important parameters such as temperature, pH, ammonia and dissolved oxygen. The automated control system can regulate ventilation, oxygen injection and even feeding based on these parameters. This automation integration allows the RAS system to maintain environmental stability and improve operational efficiency, fish growth and disease resistance.

Recirculating Aquaculture Systems (RAS) utilize several advanced water treatment technologies to maintain water quality and effectively manage waste. Technologies such as mechanical filters, protein skimmers, biofiltration and collaborative UV irradiation contribute to the aquatic system's overall efficiency.

One of the main components of RAS is the biofiltration system, which is crucial. Biofiltration decomposes organic waste and nitrogen, such as ammonia, into a non-toxic form for fish. The use of various biofilters, including fluidized sand biofilters and moving bed biofilm reactors, effectively removes harmful nitrogen and other substances from wastewater [5]. By reducing the accumulation of harmful materials, biofiltration helps to maintain stable water quality and fish health.

Biofilter media in Recirculating Aquaculture Systems (RAS) plays an important role in nitrification, a key step in removing toxic ammonia and nitrite from water. In RAS systems, biofilters provide a conducive environment for the growth of nitrifying bacteria that convert the ammonia metabolic product of fish into nitrite and nitrate, which is less harmful to fish. Research results show that ammonia oxidizing bacteria such as Nitrosomonas and nitrite oxidizing bacteria such as Nitrobacter are very important in the nitrogen removal capacity of the biofilter, which supports optimal water quality for fish farming [6]. Using effective biofilter media, such as ceramic or bioballs, RAS systems can reduce the risk of toxin accumulation in water while creating a healthy environment for fish growth.

Apart from improving water quality, biofilter media also plays an important role in maintaining microbiological balance in the system. The presence of various microbes in the biofilter can help control pathogens and improve overall fish health. The results of the study showed the impact of oxygenated and non-oxygenated biofilters in the wastewater treatment of recirculating aquaculture systems, revealing that biofilters play an important role in reducing ammonia and nitrite levels in water, which are essential for fish health [7]. With proper selection and management of biofilters, RAS systems can be operated successfully, enabling higher and healthier grouper productivity. In addition, innovations in biofilter media design, such as the use of foam glass, have been shown to improve efficiency in managing water quality in the systems [8].

In developing this more integrated system, RAS also utilizes protein skim to remove waste solids from the water and other temperature control and pH value regulation technologies. Stickney and Gatlin note that this integrated approach is critical to maintaining optimal environmental quality for fish growth, indirectly affecting the growth performance and health of fish in the system. Meanwhile, real-time water quality monitoring is necessary to ensure that important parameters are always within the optimal range for successful fish farming in RAS [9], confirming that water treatment technologies in RAS are efficient and essential for aquaculture sustainability.

In addition, UV irradiation is used as a water disinfection method. UV ensures the control of pathogenic microorganisms, improving the quality of fish-fed water. The results of the study showed the effectiveness of using a combination of filtration and UV irradiation in water treatment, such as in the application of a water ballast system, which significantly improved water quality [10]. This effectiveness is important in preventing the spread of disease within RAS systems, especially in the culture of fish that are susceptible to infection.

Benefits of RAS technology in grouper cultivation

The benefits of using RAS technology in grouper fish farming can be seen in the biological effects on fish, feed efficiency, increased nutritional content in fish and environmental improvement. The explanation of the benefits of using RAS technology is as follows.

Improved Growth Performance and Feed Efficiency

Recirculating Aquaculture System (RAS) allows for better environmental control, including temperature, dissolved oxygen and other water quality parameters significantly affecting fish growth. The use of nanobubble technology in the RAS system increases the solubility of oxygen in water which directly contributes to the average daily growth of grouper seeds (*Epinephelus fuscoguttatus* × *E. microdon*) [3]. The high availability of oxygen in the RAS helps reduce physiological stress and increase fish appetite, resulting in more efficient feed conversion (FCR) than open systems. The use of a RAS system with nanobubble technology (NBs) provides better feed conversion ratio (FCR) efficiency in grouper fry culture, where the best results were obtained in the 5RN treatment (RAS with NBs and stocking density of 500 fish/m^3) with an FCR value of 1.04 ± 0.01. This value indicates that the fish in the system can convert feed into biomass more efficiently than the other treatments.

Apart from oxygen, stocking density management also plays an important role. Increased stocking densities in RAS can be maintained without reducing growth rates if water quality is strictly controlled [11]. This is in contrast with conventional systems, where an increase in stocking density tends to cause a drastic decline in growth performance and water quality. RAS can support intensive production with higher space efficiency, making it ideal for areas with limited land and water.

Grouper culture in RAS can maintain growth throughout the year, even when there are seasonal fluctuations or unfavorable weather in conventional systems [2]. The availability of a stable environment in RAS encourages fish to focus their energy on growth and nutrient absorption rather than responding to environmental stress. These advantages in feed efficiency and growth in RAS provide a strong basis for expanding the application of this technology to the grouper fry and enlargement industry that demands consistent, high-quality results.

Although RAS offers a wide range of advantages, challenges remain, especially in the optimal management and maintenance of the system. Poor water quality can slow fish growth and reduce feed efficiency, so proper monitoring and control should be a priority [12]. New technologies in water treatment in this context, such as RAS, create opportunities to improve grouper performance and contribute to developing more sustainable and environmentally friendly aquaculture.

Table 3: Growth Indicators of Grouper Fish Cultured in Different Systems [3]

Treatment	Initial length	Final Length	Initial weight	Final weight	SGR (%/day)	FCR
5R	3.52±0.04[a]	7.55±0.27[a]	0.99±0.03[a]	8.95±0.92[a]	3.67±0.17[a]	1.13±0.16[ab]
6R	3.5±0.08[a]	7.56±0.15[a]	1.00±0.08[a]	8.5±0.22[a]	3.57±0.16[a]	1.32±0.17[bc]
7R	3.52±0.07[a]	7.36±0.09[a]	0.97±0.02[a]	8.16±0.84[a]	3.55±0.18[a]	1.57±0.14[d]
5RN	3.51±0.06[a]	8.86±0.03[b]	0.99±0.02[a]	12.2±0.01[b]	4.19±0.04[b]	1.04±0.01[a]
6RN	3.55±0.02[a]	8.92±0.02[b]	0.94±0.03[a]	12.03±0.58[b]	4.25±0.07[b]	1.11±0.06[ab]
7RN	3.54±0.04[a]	8.93±0.04[b]	0.96±0.03[a]	12.35±0.47[b]	4.25±0.09[b]	1.27±0.06[b]
5K	3.49±0.05[a]	7.56±0.26[a]	0.97±0.03[a]	8.86±0.21[a]	3.69±0.08[a]	1.53±0.13 [cd]
6K	3.46±0.01[a]	7.33±0.36[a]	1.02±0.09[a]	8.27±0.48[a]	3.49±0.04[a]	1.55±0.15[cd]
7K	3.51±0.04[a]	7.34±0.21[a]	0.96±0.02[a]	8.33±0.36[a]	3.6±0.04[a]	1.51±0.13[d]

Different superscript letters after average ± standard error values in the same column show a significant difference (P>0.05). SGR: Specific growth rate and FCR: Feed convention ratio.

Source: Hanif et al. [3]

Table 3. shows the effect of culture system and stocking density on length, weight, specific growth rate (SGR) and feed conversion ratio (FCR) of grouper. In general, the RAS system with added nanobubbles (marked RN) showed the best performance, especially in the 6RN treatment which produced the highest final weight (12.03 ± 0.58 g), highest SGR (4.25 ± 0.07%/day) and lowest FCR (1.11 ± 0.0.06), indicating optimal growth and feed efficiency. In contrast, the conventional system (K) showed lower performance, with decreased SGR and feed efficiency. This confirms that the RAS system, especially with innovations such as nanobubbles, can create more stable and efficient environmental conditions for grouper growth.

Fish Health and Disease Resistance.

One of the advantages of the RAS system is its ability to consistently maintain water quality, which directly affects the physiological and immune conditions of fish. The results of the study showed a comparison of European catfish (*Silurus glanis*) cultured in a Recirculating Aquaculture System (RAS) compared to a traditional earthen pond system revealed that fish cultured in RAS showed significantly better hematological parameters, including higher hemoglobin concentrations and higher white blood cell counts, as well as better serum biochemical profiles, such as increased levels of total protein, albumin and globulin [13]. These findings suggest that RAS provides a more stable and controlled environment, leading to better physiological health and possibly increased disease resistance in farmed fish.

Although this study focuses on European catfish, the implications are relevant for other aquaculture species, such as grouper. The better health indicators observed in fish farmed in RAS emphasize the potential of these systems to improve fish welfare and productivity. By minimizing environmental stress and maintaining optimal water quality, RAS can contribute to aquaculture species' overall resistance and resilience to disease.

Gut microbiota and the immune system in fish have a close relationship. The usual decrease in microbial diversity due to infection can lead to a less effective immune response, affecting the fish's ability to fight pathogens. In addition, identified pathogenic bacteria, such as Acinetobacter spp., can lead to more widespread disease outbreaks, demonstrating the importance of comprehensive health management strategies in aquaculture to prevent infections. The study provided valuable insights that RAS monitoring of the microbiome aspects of grouper health management can be maintained, resulting in a healthy microbiota balance and a strengthened immune response in fish [14].

Recirculating Aquaculture System (RAS) technology has been proven to provide better health growth in groupers. In RAS, the concentration of pathogenic bacteria such as Vibrio can be significantly reduced compared to conventional pond culture systems. This is due to the water quality maintained through effective filtration and treatment in RAS, thus ensuring cleaner environmental conditions for fish [15]. Research shows that with strict control of environmental parameters, fish can grow healthier and have better disease resistance [16]. This result aligns with the finding that disease prevalence in groupers in RAS can be significantly reduced, leading to reduced mortality and profits for fish farmers [17].

Figure 39 shows the number of microbial colonies (CFU/ml) detected in the water and effluent from the Tilapia and Clarias RAS systems, using three types of media: TSA (common bacteria), MA (fungi) and KB (fluorescent pseudomonads). The results showed that colony counts on TSA and KB were relatively high and uniform across all treatments, indicating the dominance of typical bacterial flora and pseudomonads. In contrast, MA showed significantly lower colony counts (different letters), indicating that the fungal population in the RAS environment was much less than that of bacteria. There were no significant differences between fish species or water and effluent in TSA and KB medium, indicating the stability of specific microbial communities in the RAS system. This supports the efficiency of the microbial biofilter in treating effluent in the recirculation system.

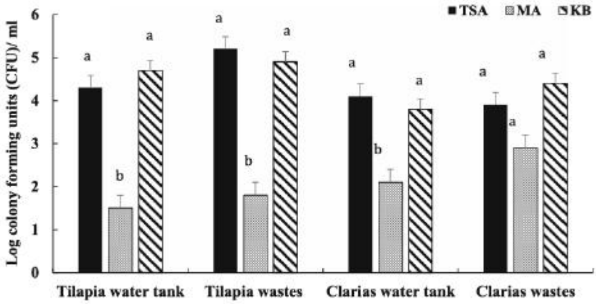

Fig 39: The number of microbial colonies (CFU/ml) detected in the water and waste from the RAS system [15]

Treatments

From water and waste samples of Tilapia and Clarias RAS, microbial colonies were isolated and counted on 0.1% Tryptic soya agar (TSA) supplemented with 100 µg mL-1 for the general bacterial flora, 0.5% malt extract agar (MA) for the general fungal flora and on King Agar B (KB) supplemented with 100 µg mL-1 for the fluorescent pseudomonads. Significant differences between the treatments are indicated by letters above the bars.

Source: Khalil et al. [15]

Superior Nutritional Quality

RAS (Recirculating Aquaculture System) technology in grouper aquaculture has shown significant advantages in increasing the amino acid content and beneficial fatty acids, contributing to better nutritional value and flavor of the fish. The quality of feed used in RAS systems plays an important role in improving the amino acid profile, which is recognized as an essential nutrient for fish growth and health [1]. Through better control of diet and water quality, groupers farmed in RAS have a more balanced composition than fish obtained from conventional pond systems, where feed quality and environment variations cannot always be prevented.

Table 4 shows the amino acid composition of grouper muscle cultured in two systems, namely SPS (conventional) and RAS (Recirculating Aquaculture System). The analysis showed that most of the amino acids, both essential (EAA) and nonessential (NEAA), had equivalent or slightly higher values in fish from the RAS system. However, the differences were not statistically significant for most parameters. Essential components such as glutamic acid, glycine, lysine and leucine, which play a role in meat quality and growth, were also slightly higher in fish from RAS. The total EAA and TAA (total amino acid) values also showed a higher trend in RAS fish, at 26.63% and 71.32%, compared to 26.00% and 70.47% in SPS. This indicates that the RAS system can produce fish with a better muscle protein profile, thus potentially producing fish products of higher nutritional quality.

Table 4: The amino acid composition in the muscle of grouper fish in two systems, namely SPS (conventional) and RAS.

Amino acids	SPSS	RAS
Taurine	0.93±0.06	0.96±0.06
Aspartic acid	7.88±0.01	7.80±0.02
Threonine	3.26±0.02[a]	3.44±0.02
Serine	3.48±0.05[a]	3.06±0.07
Glutamic acid	11.92±0.32	11.69±0.49
Glycine	3.43±0.03[a]	4.15±0.13
Alanine	4.45±0.19	4.49±0.28
Cysteine	1.78±0.11	1.78±0.15
Valine	2.77±0.02[a]	2.60±0.07
Methionine	2.29±0.02	1.98±0.10
Isoleucine	2.61±0.32	2.56±0.04
Leucine	5.70±0.14	5.52±0.19
Tyrosine	2.56±0.06[a]	2.27±0.01
Phenylalanine	3.03±0.08	2.96±0.11
Lysine	6.87±0.14	6.69±0.27
Histidine	1.43±0.02[a]	1.82±0.06
Arginine	4.27±0.08	4.16±0.13
Proline	2.33±0.07[a]	2.41±0.13
Tryptophan	3.57±0.3	4.05±0.72
EAA	26.00±0.27	26.63±0.21
NEAA	20.60±0.20[a]	21.85±0.25
DAA	27.31±0.26[a]	28.66±0.03
TAA	70.47±0.52	71.32±0.88

[a]indicates a significant difference ($P<0.05$). EAA refers to the total content of essential amino acids; NEAA refers to the total content of non essential amino acids; DAA represents the total content of delicious amino acids and TAA refers to the total amino acid content.

Source: Qu et al, 2024 [1]

The mechanism of the Recirculating Aquaculture System (RAS) in optimizing nutrient absorption in fish is greatly influenced by its ability to maintain consistent water quality. Consolidated oxygen, temperature and stable pH are important elements in creating an ideal aquaculture environment. This maintained water quality plays an important role in reducing fish metabolic stress, which can increase nutrient absorption efficiency. The RAS system can reduce stress in fish through tight control of environmental parameters, which in turn supports the availability and absorption of nutrients in the fish's body [18]. In an optimized environment, digestive and metabolic processes in fish run more efficiently, allowing for improved growth and overall health.

In addition, RAS exhibit lower feed conversion ratio (FCR) and higher daily growth than open systems. In other words, the controlled water quality in RAS creates optimal conditions that allow fish to absorb and utilize nutrients to their full potential, making it a highly effective and efficient system supporting sustainable aquaculture productivity. This is important, given the increasing consumer interest in healthy and nutritious food. By reducing reliance on fishmeal and substituting it with alternative feed sources, such as microalgae, RAS technology improves nutritional yield and provides a sustainable solution for the aquatic industry [19].

The flavor quality of grouper farmed in RAS is often considered superior to that of fish farmed in open ponds. Several studies have shown that more stable environmental factors in RAS systems contribute to improved organoleptic characteristics of fish. Fish cultured using the RAS system show better meat quality, including taste, compared to fish from conventional pond systems [13]. Better control of water quality and nutrients in RAS positively influences fish growth and metabolism, resulting in higher flavor quality meat.

Environmental Sustainability

Recirculating Aquaculture Systems (RAS) offer innovative solutions to minimize water use and reduce environmental pollution through effective water recycling and waste management, making them a more sustainable option for aquaculture. Using RAS, only a fraction of the water is required compared to traditional culture systems in open ponds. A study [20] showed that the design of RAS systems can significantly reduce the amount of water required to culture fish while performing waste treatment in a closed and controlled system [20]. In addition to effective treatment of effluents such as ammonia, RAS also minimizes water usage.

In the RAS system it was shown that microalgae used in RAS wastewater treatment can absorb nitrogen and phosphorus, thereby reducing the potential for environmental contamination [21]. In addition, effective management of solid and liquid wastes in RAS reduces the amount of harmful compounds released into the environment, which is one of the leading causes of eutrophication. Using water recycling systems and efficient waste treatment techniques, RAS offers a sustainable solution that benefits fish productivity and maintains a balanced ecosystem quality around the aquatic system.

Figure 40 compares the concentrations of various nitrogen, phosphorus and sulfur forms in wastewater from a recirculating aquaculture system (RAS) before and after N. link culture. The gray columns represent the control values before cultivation, while the black columns show the concentrations after cultivation. Asterisks (*) indicate significant differences in values after culture compared to the control, with higher concentrations for nitrate (NO_3^-) and sulfate (SO_4^{2-}). This study indicates that N. linckia culture can contribute to changes in wastewater quality, potentially improving nutrient efficiency in aquaculture systems.

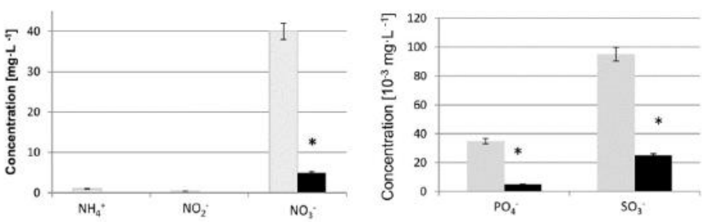

Fig 40: Comparison of the concentrations of various forms of nitrogen, phosphorus and sulfur in wastewater from a recirculating aquaculture system (RAS) before and after cultivation.

Source: Cheban *et al.* [21]

RAS also supports the circular economy approach in aquaculture, where waste from fish can be repurposed as inputs for crop production in aquaponics systems [22]. By integrating fish farming with agriculture, RAS not only optimizes the use of water resources but also improves nutrient use efficiency. This suggests that RAS can be a more environmentally friendly model for sustainable food production and help improve global food security.

Economic Advantage and Scalability

Recirculating Aquaculture Systems (RAS) have been proven to be economically feasible, especially in the context of grouper fish farming. The results of the study revealed that RAS can provide a high level of profit in catfish cultivation, which of course can be applied to other species, such as grouper [23]. The key to the economic viability of RAS lies in important parameters such as price, production yield, cost of seed, feed and initial investment. With efficient management, RAS can reduce operational costs, increase productivity and optimize resource use.

Furthermore, costs associated with fish medication and disease management in RAS are usually lower than in conventional aquaculture systems, where diseases often cause significant losses due to mortality. Strict environmental control in RAS can reduce stress on fish and increase growth rates, positively impacting overall economic outcomes. In addition, using more efficient and innovative technologies in RAS, such as computer vision-based intelligent feed systems, can further improve productivity through more accurate feeding [24].

RAS systems also reduce dependence on water resources, enabling water recycling, which reduces operational costs and environmental impact. In addition, RAS designs can be customized to increase fish density, which contributes to greater production output by utilizing a smaller area of land. With all these factors, RAS becomes an option that is both sustainable from an environmental perspective and economically viable.

Conclusion

Recirculating Aquaculture System (RAS) technology significantly improves production efficiency, fish health and environmental sustainability in grouper farming. RAS can improve fish growth performance and feed efficiency through optimal water quality control and advanced filtration systems while minimizing waste and water usage. Literature studies show that implementing RAS supports disease resistance and creates a more stable aquaculture environment. From an economic and ecological perspective, RAS has excellent potential as a modern aquaculture production system capable of meeting global market demands while maintaining environmental balance.

References

1. Qu Y, Yin Z, Fan X, Hu H, Cui H, Cui Z *et al*. A comparative analysis of growth and nutritional quality of the hybrid grouper (Epinephelus fuscoguttatus ♀ × Epinephelus lanceolatus ♂) in a simulated pond system and a recirculating aquaculture system. Front Mar Sci 2024;11:1378735. https://doi.org/10.3389/fmars.2024.1378735.
2. Ranjan R, Megarajan S, Xavier B, Dash B, Ghosh S, Menon M *et al*. Conditioning, maturation and year-round natural spawning of orange-spotted grouper, Epinephelus coioides (Hamilton, 1822), in recirculating aquaculture system. Aquac Res 2017;48:5864–73.

https://doi.org/10.1111/are.13409.

3. Hanif IM, Effendi I, Budiardi T, Diatin I. The recirculated aquaculture system (RAS) development with nanobubble application to improve growth performance of grouper fish fry culture. Jurnal Akuakultur Indonesia 2021;20:181–90. https://doi.org/10.19027/jai.20.2.181-190.
4. Hsu TH, Chiu YT, Lee HT, Gong HY, Huang CW. Development of EST-Molecular Markers from RNA Sequencing for Genetic Management and Identification of Growth Traits in Potato Grouper (*Epinephelus tukula*). Biology 2021; 10:36. https://doi.org/10.3390/biology10010036.
5. Xiao R, Wei Y, An D, Li D, Ta X, Wu Y *et al*. A review on the research status and development trend of equipment in water treatment processes of recirculating aquaculture systems. Reviews in Aquaculture 2019;11:863–95. https://doi.org/10.1111/raq.12270.
6. Huang PL, Afero F, Chang Y, Chen BY, Lan HY, Hou YL *et al*. The Bioeconomic Analysis of Hybrid Giant Grouper (Epinephelus fuscoguttatus × Epinephelus lanceolatus) and Green Grouper (Epinephelus malabaricus): A Case Study in Taiwan. Fishes 2023; 8:610. https://doi.org/10.3390/fishes8120610.
7. Gichana Z, Liti D, Drexler SS, Zollitsch W, Meulenbroek P, Wakibia J *et al*. Effects of aerated and non-aerated biofilters on effluent water treatment from a small-scale recirculating aquaculture system for Nile tilapia (*Oreochromis niloticus L.*). Die Bodenkultur: Journal of Land Management, Food and Environment 2019; 70:209–19. https://doi.org/10.2478/boku-2019-0019.
8. Sharylo D, Kovalenko V. Efficiency of using foamed glass for biofilter of an aquaculture recycling system. ASaFT 2022; 3:53–8. https://doi.org/10.31548/animal.13(3).2022.53-58.
9. Lindholm-Lehto P. Water quality monitoring in recirculating aquaculture systems. Aquaculture Fish & Fisheries 2023; 3:113–31. https://doi.org/10.1002/aff2.102.
10. Wang Y, Wang Q, Dong K, Chen J, Wu H. Assessing the effectiveness of filtration + UV-C radiation for the treatment of simulated ballast water at various holding times. Water Science & Technology 2023; 87:2564–76. https://doi.org/10.2166/wst.2023.146.
11. Shao T, Chen X, Zhai D, Wang T, Long X, Liu Z. Evaluation of the effects

of different stocking densities on growth and stress responses of juvenile hybrid grouper ♀ Epinephelus fuscoguttatus × ♂ Epinephelus lanceolatus in recirculating aquaculture systems. Journal of Fish Biology 2019; 95:1022–9. https://doi.org/10.1111/jfb.14093.

12. Li H, Cui Z, Cui H, Bai Y, Yin Z, Qu K. A review of influencing factors on a recirculating aquaculture system: Environmental conditions, feeding strategies and disinfection methods. J World Aquaculture Soc 2023; 54:566–602. https://doi.org/10.1111/jwas.12976.
13. Barbacariu CA, Rimbu CM, Burducea M, Dirvariu L, Miron LD, Boiangiu RS *et al*. Comparative Study of Flesh Quality, Blood Profile, Antioxidant Status and Intestinal Microbiota of European Catfish (*Silurus glanis*) Cultivated in a Recirculating Aquaculture System (RAS) and Earthen Pond System. Life 2023; 13:1282. https://doi.org/10.3390/life13061282.
14. Xiao Joe JT, Tseng YC, Wu JL, Lu MW. The Alteration of Intestinal Microbiota Profile and Immune Response in Epinephelus coioides during Pathogen Infection. Life 2021; 11:99. https://doi.org/10.3390/life11020099.
15. Khalil S, Panda P, Ghadamgahi F, Rosberg A, Vetukuri RR. Comparison of two commercial recirculated aquacultural systems and their microbial potential in plant disease suppression. BMC Microbiol 2021; 21:205. https://doi.org/10.1186/s12866-021-02273-4.
16. Abu Aziz N, Christianus A, Wan Solahudin WMS, Ismail IS, Low C. Comparative proteome analysis revealed potential biomarkers and the underlying immune mechanisms in Vibrio -resistant hybrid grouper, Epinephelus fuscoguttatus ♀ × Epinephelus lanceolatus ♂. Journal of Fish Diseases 2024; 47:e13940. https://doi.org/10.1111/jfd.13940.
17. Yanuhar U, Nurcahyo H, Widiyanti L, Junirahma NS, Caesar NR, Sukoso S. In vivo test of Vibrio alginolyticus and Vibrio harveyi infection in the humpback grouper (Cromileptes altivelis) from East Java Indonesia. Vet World 2022; 1269–82. https://doi.org/10.14202/vetworld.2022.1269-1282.
18. Martins CIM, Eding EH, Verdegem MCJ, Heinsbroek LTN, Schneider O, Blancheton JP *et al*. New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. Aquacultural Engineering 2010; 43:83–93.

https://doi.org/10.1016/j.aquaeng.2010.09.002.

19. Chen W, Gao S. Current status of industrialized aquaculture in China: a review. Environ Sci Pollut Res 2023; 30:32278–87. https://doi.org/10.1007/s11356-023-25601-9.

20. Asiri F, Chu KH. A Novel Recirculating Aquaculture System for Sustainable Aquaculture: Enabling Wastewater Reuse and Conversion of Waste-to-Immune-Stimulating Fish Feed. ACS Sustainable Chem Eng 2020; 8:18094–105. https://doi.org/10.1021/acssuschemeng.0c06375.

21. Cheban L, Turianska Y, Marchenko M. Obtaining phycobiliprotein-containing *Nostoc linckia* (Roth.) Born. et Flah biomass via bioconversation of waste water from reticulating aquaculture systems (RAS). Nova Biotechnol Chim 2020; 19:240–7. https://doi.org/10.36547/nbc.v19i2.592.

22. Lal J, Vaishnav A, Deb S, Kashyap S, Debbarma P, Devati *et al*. Re-Circulatory Aquaculture Systems: A Pathway to Sustainable Fish Farming. Arch Curr Res Int 2024; 24:799–810. https://doi.org/10.9734/acri/2024/v24i5756.

23. Ngoc PTA, Meuwissen MPM, Cong Tru L, Bosma RH, Verreth J, Lansink AO. Economic feasibility of recirculating aquaculture systems in pangasius farming. Aquaculture Economics & Management 2016; 20:185–200. https://doi.org/10.1080/13657305.2016.1156190.

24. An D, Hao J, Wei Y, Wang Y, Yu X. Application of computer vision in fish intelligent feeding system—A review. Aquac Res 2021; 52:423–37. https://doi.org/10.1111/are.14907.

12

CHAPTER

Revolutionizing Shrimp Farming: The Promise and Challenges of Recirculating Aquaculture Systems (RAS) for *Litopenaeus vannamei* in The Tropics

Eddy Supriyono
Department of Aquaculture, Faculty of Fisheries and Marine Science, Bogor Agricultural University (IPB University), West Java, Indonesia

Lolita Thesiana*
Research Center for Fishery, National Research and Innovation Agency (BRIN), Cibinong Science Center - Cibinong, Nanggewer Mekar, Bogor, West Java, 1692, Indonesia

Kukuh Adiyana
Research Center for Fishery, National Research and Innovation Agency (BRIN), Cibinong Science Center - Cibinong, Nanggewer Mekar, Bogor, West Java, 1692, Indonesia

Kukuh Nirmala
Department of Aquaculture, Faculty of Fisheries and Marine Science, Bogor Agricultural University (IPB University), West Java, Indonesia

Moh Burhanuddin Mahmud
Department of Aquaculture, Faculty of Fisheries and Marine Science, Bogor Agricultural University (IPB University), West Java, Indonesia

Tuti Wahyuni
Research Center for Agroindustry, National Research and Innovation Agency (BRIN), Indonesia

Corresponding Author: loli002@brin.go.id

Abstract

The Pacific white shrimp (*Litopenaeus vannamei*) plays a crucial role in the global aquaculture industry, particularly in tropical and subtropical regions. Growing global demand has driven the adoption of increasingly intensive production systems. However, conventional intensive methods face sustainability challenges, including limited land and water resources, nutrient rich waste discharge and disease outbreaks. Recirculating Aquaculture Systems (RAS) have emerged as an advanced land-based farming technology, offering improved water quality control, an essential factor for shrimp health and growth. Recent research on *Litopenaeus vannamei* culture in RAS has focused on technological innovations, water quality management, disease control, stocking density optimization, growth performance, feeding strategies and integration with Integrated Multi-Trophic Aquaculture (IMTA) systems. Various RAS configurations have been developed, including standard RAS, hybrid biofloc-RAS, zero water discharge RAS (ZWD-RAS), low salinity RAS and nursery systems. RAS offers advantages in disease control through enhanced water quality management and microbial community regulation, employing technologies such as ozonation and biofiltration. While RAS supports high stocking densities, there are thresholds beyond which individual performance declines. Additionally, the use of color in rearing systems has been shown to influence shrimp production performance. Key challenges to implementing RAS in tropical regions include managing water quality at high temperatures, endemic diseases, salinity regulation and vulnerability to extreme weather and climate change.

Keywords: *Litopenaeus vannamei*, RAS, intensive shrimp farming, tropical aquaculture, zero water discharge, Integrated Multi-Trophic Aquaculture (IMTA).

Introduction

The Pacific white shrimp plays a pivotal role in the global aquaculture industry, ranking among the most dominant species in farmed shrimp production worldwide [1]. The success of *Litopenaeus vannamei* aquaculture is primarily attributed to several key biological characteristics, including its rapid growth rate, broad environmental adaptability, particularly its tolerance to a wide range of salinity levels, ease of controlled breeding and consistently high market demand [1]. Geographically, the production of Pacific white shrimp is concentrated in tropical and subtropical regions, with countries in Asia and Latin America serving as the primary producers [1].

The rising global demand for shrimp has driven the aquaculture industry toward increasingly intensive production systems [2]. However, conventional intensive farming methods, particularly those based on earthen ponds, face numerous sustainability challenges. Key issues include limited availability of land and water resources, the discharge of nutrient rich effluents into surrounding ecosystems [3] and the growing incidence of disease outbreaks, especially those caused by Vibrio pathogens [4]. Furthermore, the expansion of shrimp ponds has often been associated with the degradation of critical habitats, such as mangrove forests [5]. In response to these concerns, developing sustainable intensive farming systems has become a central focus of technological innovation in aquaculture.

Recirculating Aquaculture Systems (RAS) have emerged as an advanced landbased aquaculture technology that offers a promising solution to the challenges of intensification and sustainability in shrimp farming [6]. RAS allows for enhanced control over water quality, which is a critical factor in cultivating shrimp [7]. Poor water quality can profoundly affect shrimp health, hinder growth performance and, in severe cases, result in mass mortality events [8]. Suboptimal water conditions heighten the susceptibility of *Litopenaeus vannamei* to infections caused by *Vibrio* species, which are associated with significant growth retardation and elevated mortality rates [9]. Recirculating aquaculture systems offer a more controlled biosecure rearing environment by stabilizing key water quality parameters such as dissolved oxygen (DO), pH and ammonia levels. For example, maintaining DO concentrations above 3 mg/L is critical to minimizing stress related mortality and ensuring optimal growth in shrimp culture [10, 11]. Furthermore, declines in pH and increases in water temperature have also been reported to negatively affect the growth performance of Pacific white shrimp (*Litopenaeus vannamei*) [12].

Recent studies on *Litopenaeus vannamei* cultivation using RAS have focused on a range of key areas, including technological innovations, water quality management, disease control and health management, stocking density optimization, growth performance and feeding strategies, as well as the integration of RAS with Integrated Multi Trophic Aquaculture (IMTA) systems. These studies showed RAS's diverse capacity to improve the effectiveness and sustainability of shrimp culture. Nevertheless, further comprehensive evaluations are important to identify the existing obstacles and potential prospects in RAS development, particularly in enhancing the productivity of Pacific white shrimp farming.

RAS Technology Innovation and System Design for Vannamei Farming

The implementation of RAS specifically for *Litopenaeus vannamei* farming in tropical countries was initiated more than 10 years ago. Relevant case studies have been reported from a variety of locations, including India [13], Indonesia [14, 15], Vietnam [5], Thailand [16], Brazil [17] and Ecuador [18]. These studies range from experimental and pilot scale trials to commercial scale implementations, reflecting a growing interest in adapting RAS technology for Pacific white shrimp aquaculture. A comprehensive range of

RAS design variations has been formulated or assessed to meet tropical regions' specific requirements and environmental contexts, underscoring both the technological adaptability and the site specific considerations requisite for successful implementation.

- Standard RAS: This configuration employs conventional RAS components such as mechanical filtration, biofiltration, oxygenation units and water recirculation pumps. It serves as a baseline model for land-based shrimp farming and has been successfully applied [14, 17].
- Hybrid Biofloc-RAS: This system integrates biofloc technology, which promotes the *in situ* development of microbial flocs within the culture tank, with external RAS components. The biofloc contributes to improved nitrification capacity and provides supplementary nutrition for shrimp. Furthermore, the potential of this hybrid system demonstrated on enhance both water quality management and feed efficiency [19]. A study on land based cultivation of *Litopenaeus vannamei* employing a hybrid Biofloc-Recirculating Aquaculture System (Biofloc-RAS) [19], utilizing concrete culture tanks, a sedimentation pond and an aerated nitrification biofilter filled with high density polyethylene media. The aggregate water capacity within a singular unit of this system is 30 m^3, outfitted with a circulation pump proficient in delivering approximately 6- 12 m^3 of water per hour. Shrimp juveniles with an average initial body weight of 1.92 ± 0.43 g were stocked at a density of 300 individuals/m^3 for the production trial. The initial water composition comprises 90% seawater (27 m^3) that has undergone sand filtration and chlorination and 10% biofloc rich water (3 m^3) sourced from a shrimp nursery pond. Shrimp were cultured for 70 days, during which daily increments of molasses were introduced to the culture tank to attain a ratio of C: N 12:1. The finding of this study indicated that inoculating the culture tanks with biofloc rich water significantly accelerated the nitrification start-up phase, achieving Total Ammonia Nitrogen (TAN) removal rates exceeding 6.28 mg/L/day with efficiency surpassing 92.2% throughout the stabilization phase. Shrimp production performance in this system was also notably high, encompassing an average growth rate of 2.15±0.18 g/week, a survival rate of 93.11±1.66 %, a yield of 4.98±0.10 kg/m^3 and a feed conversion ratio (FCR) of 1.60±0.03. Overall, the hybrid Biofloc-RAS system has proven feasible and effective for promptly removing

continuously generated ammonia, even under high feed input conditions and without water exchange [18]. The production performance attained is also comparable to findings from other investigations on a commercial scale for intensive cultivation of *Litopenaeus vannamei*, in both bioflock-based systems, RAS and hybrid RAS.

- Zero Water Discharge RAS (ZWD-RAS): Designed for nearly 100% water reuse, this system minimizes or eliminates effluent discharge by incorporating biofloc or other nutrient recovery mechanisms. The ZWD-RAS model, as implemented in Indonesia, represents a sustainable approach particularly suited for regions facing water scarcity or strict environmental regulations [15].
- Low-Salinity RAS: This system operates at reduced salinity levels, typically between 5–15 ppt and is often employed for inland aquaculture operations far from seawater sources. Effective implementation of low-salinity RAS requires precise water ionic composition management to support shrimp health and performance. A research [20] contrasted the productivity efficacy of *Litopenaeus vannamei* and water quality fluctuations in terrestrial recirculation systems utilizing different formulations of lowest-cost salt mixes (LCS) and commercial comprehensive sea salt formulations (CSS). The RAS setup encompasses a 1000 liter rearing tank, each outfitted with the same volume of settling chamber and biological filtration unit (each 18 liters). The biological filters were aerated moving bed biofilm reactors (MBBRs) employing Curler Advance X-1 media (Aquaculture Systems Technologies, LLC., New Orleans, LA, USA.). At the commencement of the study, 3 liters of biomedia were incorporated from the established shrimp culture pond to expedite the colonization of microorganisms within the system. Water circulation from the rearing tanks to the settling chambers was facilitated by a submersible pump with a flow rate of 20 liters per minute, while water flow from the settling chamber to the biofilter relied on gravity. The system also had a water heater to maintain a stable temperature. At the commencement of the trial, shrimp average initial weight was 2.9 g/shrimp, stocked at a density of 262 shrimp/m^3 and were cultured at a salinity of 15 ppt using six different LCS to CSS mixing ratios: 100% LCS, 97.5% LCS, 95% LCS, 90% LCS, 80% LCS and 75% LCS. The trial lasted for 86 days.

The result of water quality observations showed no significant differences among treatments in terms of temperature, total ammonia nitrogen (TAN), nitrite, total suspended solids (TSS) or volatile suspended solids (VSS). Average TAN concentrations ranged from 0.6±0.2 to 0.8±0.2 mg/L and nitrite levels ranged from 0.8±0.2 to 0.9±0.2 mg/L. However, salt formulation significantly impacted dissolved oxygen (DO), pH, salinity and turbidity throughout the study. DO levels tended to increase as the proportion of CSS decreased, with the 100% LCS and 97.5% LCS treatments exhibiting significantly higher DO levels compared to the other four treatments19. Average DO levels ranged from 6.4±0.1 to 6.5±0.0 mg/L. The 100% LCS treatment showed a significantly lower overall pH than the 90% LCS and 80% LCS treatments. The average pH across all treatments was 7.9±0.0.

Regarding production performance, no significant differences were observed among treatments in average shrimp weight, biomass, survival rate, feed conversion ratio (FCR) or growth rate. The average shrimp harvest weight ranged from 20.7±0.3 g to 22.2±0.6 g, while the average growth rate ranged from 1.4±0.0 to 1.6±0.1 g/week. FCR values ranged from 1.4±0.1 to 1.6±0.1. Shrimp biomass production ranged from 4.3±0.4 to 4.7±0.2 kg/m^3. The average survival rate across all treatments was 81%, ranging from 76.7±5.8% to 84.3±3.2%. From a cost perspective, LCS formulations significantly reduced the salt cost per kilogram of shrimp produced. The lowest salt cost was observed in the 97.5% LCS treatment ($2.03/kg shrimp), which was significantly lower than the 80% LCS ($2.63) and 75% LCS ($2.76) treatments. This study demonstrates the feasibility and cost effectiveness of using easily prepared, low cost salt mixtures for intensive indoor shrimp production. LCS mixtures are recommended for shrimp producers due to the substantial reduction in production costs, while maintaining shrimp performance and water quality comparable to those achieved with commercial sea salt mixtures.

- Nursery Systems: This application uses RAS principles, such as limited water exchange and biofiltration, during the intensive nursery phase to produce larger, more resilient juveniles before transfer to grow-out systems. A study on shrimp nursery within a recirculating aquaculture system (RAS) with a total volume of 600 L and water circulation was maintained using a 0.75 hp centrifugal pump at a flow rate of 180 L/h was conducted for the rearing of postlarvae [7]. The water treatment system consisted of a mechanical bubble bead and biological filter using K1 Kaldnes media. A commercial probiotic, Sanolife MIC, was administered daily at a 3 g/m^3 dose to maintain optimal microbial conditions within the system. The results indicated that the system effectively controlled nitrogenous compounds, including TAN, NO_2^--N and NO_3^--N, due to the continuous mechanical and biological filtration processes. Moreover, the system supported a shrimp survival rate of 88 %. RAS provides a robust framework for sustainable and intensive *Litopenaeus vannamei* nursery operations, optimizing environmental conditions and economic outcomes [7].

- Integrated Multi-Trophic Aquaculture (IMTA): The study on evaluating the use of a recirculating system with a settling chamber in a synbiotic IMTA setup involving juvenile *Crassostrea sp.* and *Litopenaeus vannamei* post-larvae and the results demonstrated that IMTA treatments produced significantly lower levels of settleable solids compared to monoculture. Moreover, shrimp weight and yield (1.59 g and 4.63 kg/m^3, respectively) and oyster weight (18.05 g) were significantly higher in the IMTA system, indicating enhanced performance under integrated conditions [21]. Another research also compared the co culture of *Litopenaeus vannamei* and razor clam (*Sinonovacula constricta*) under two production modes: traditional polyculture and tandem mariculture pond systems. The results showed that both shrimp and clam yields were significantly higher ($p < 0.05$) in the tandem culture system (clam: 6.81 ± 0.38 kg/m^2; shrimp: 1.24 ± 0.06 kg/m^2) compared to the traditional polyculture (clam: 0.77 ± 0.06 kg/m^2; shrimp: 0.47 ± 0.03 kg/m^2) [22]. Unlike the polyculture system, which experienced severe eutrophication during the study period, the tandem system maintained better water quality. This improvement was attributed to spatial segregation of species, which reduced direct competition and organic waste accumulation in the clam habitat and more efficient nutrient utilization. Integrating multi-trophic culture systems involving *Litopenaeus vannamei* and compatible species can enhance water quality and promote better shrimp growth performance compared to conventional monoculture or polyculture approaches.

Disease Control and Health Management

Recirculating Aquaculture Systems offer several advantages for disease control in *Litopenaeus vannamei* culture, primarily through enhanced water quality management and microbial community regulation. These systems are designed to maintain optimal conditions for shrimp health by integrating various water treatment technologies, such as ozonation and biofiltration, which can effectively reduce pathogenic bacteria and stabilize the microbial environment. Ozone, a powerful oxidizing agent, is commonly applied in RAS to suppress pathogenic bacteria such as *Vibrio parahaemolyticus*. A residual ozone concentration (ROC) of 0.3 mg/L can eliminate Vibrio pathogens without affecting biofilter nitrification process, leading to maintaining water quality and ensuring shrimp safety [23].

Compared to ultraviolet (UV) radiation, ozonation has been shown to better stabilize microbial communities within RAS, prevent nitrite accumulation and accelerate nitrate degradation factors crucial for maintaining a healthy environment for shrimp [24]. In addition, peracetic acid (PAA), a potent disinfectant, can be applied in RAS. However, its use at specific concentrations may negatively affect water quality and shrimp health. Therefore, PAA application is generally recommended only for short-term treatment during disease outbreaks [24].

The integration of electrocoagulation and filtration systems in RAS can enhance the removal efficiency of total suspended solids, chemical oxygen demand, ammonia and nitrite, thereby improving overall water quality and reducing disease risks [25]. Although RAS offers significant advantages in disease control for Pacific white shrimp culture, it is important to consider potential challenges and limitations. For instance, the capital costs for implementing and maintaining RAS can be high and the system requires careful management to prevent issues such as biofilter clogging or imbalances within the microbial community.

Stocking Density, Growth Performance and FCR Values

RAS based shrimp farming technology can support high stocking densities; however, there is a practical threshold beyond which individual performance (growth, survival and feed conversion ratio) declines significantly, even if overall volumetric productivity (kg/m^3) may plateau or slightly decrease [13]. A low salinity RAS study [26] demonstrated that increasing shrimp density reduced harvest performance. When the stocking density was increased from 500 to 1000 PL/m^3, the final body weight decreased by 24%, the survival rate dropped by 37% and FCR increased by 55%, while the total productivity remained relatively constant (~5 kg/m^3). A similar trend was observed in India [13], where higher stocking densities resulted in lower average harvest weights. These findings highlight an economic trade off between maximizing volumetric yield and optimizing individual shrimp size, survival and feed efficiency.

The effect of color application on shrimp production performance

The application of color in shrimp culture ponds, through variations in pond bottom color and the use of carotenoid enriched feed technology, has been shown to significantly influence the production performance of *Litopenaeus vannamei*. Improvements in shrimp coloration are not only associated with consumer preference but also correlate with enhanced growth performance and survival rates. Several studies have investigated the effects of various color enhancement strategies on shrimp production. These approaches have demonstrated promising outcomes, offering aesthetic and physiological benefits for the cultured shrimp.

The study [14] investigated the effect of different tank colors (Pantone process white, Pantone neutral black U (RGB: 69,66,63), green-Pantone 348 C and blue-Pantone 3015 C) for the nursery phase of vannamei shrimp (Figure 41), which was conducted in Indonesia. The research findings indicated that tank color did not significantly affect growth performance. However, it significantly influenced the survival rate and metabolic activity. Tanks colored green and blue yielded better survival rates and production performance than other colors, with the highest survival rate observed in green tanks (72.92%). Furthermore, tank color also impacted the biochemical composition of the shrimp flesh, wherein shrimp reared in green tanks exhibited higher crude protein and crude fiber concentrations.

A study [27] evaluated the effect of *Bixa orellana* extract supplementation in shrimp feed within an inland biofloc system under varying levels of shading on shrimp morphological color and water quality. The extraction of *Bixa orellana* seeds yields the carotenoid bixin, which is commonly used in various industries as a natural pigment ranging from orange to deep red. The findings of this study demonstrated that the inclusion of 1.235 mg/kg bixin in shrimp feed, under 80% shading in the biofloc system, significantly enhanced the shell coloration of *Litopenaeus vannamei*, both in raw and cooked states. Furthermore, this treatment also contributed to maintaining lower ammonia concentrations in the rearing water [27].

Fig 41: Application of a recirculating aquaculture system (RAS) for Litopenaeus vannamei culture in Indonesia. The system has a total water capacity of 8.5 m^3 and is equipped with a physical filter, bioblock biofilter and microbubble technology for aeration and organic particulate removal.

Challenge to RAS technology adoption

Water Quality Management at Elevated Temperatures:

Litopenaeus vannamei is a tropical species with an optimal temperature range of 25-32°C. However, when ambient temperatures exceed this optimal threshold, it leads to an increased metabolic rate and consequently, a higher oxygen demand in shrimp [12, 28]. Concurrently, the metabolic rate of microbes within the system also tends to increase under such conditions. This situation needs a greater aeration and oxygenation capacity to maintain optimal environmental conditions, which correlates with increased energy consumption. Consequently, this demands more robust biofiltration and oxygenation capacities, rendering dissolved oxygen (DO) management more challenging due to its reduced solubility at higher temperatures. Indoor RAS might require cooling systems, significantly escalating energy costs [29]. Outdoor RAS, on the other hand, offer more limited temperature control. This interplay of factors managing temperature about oxygen solubility renders energy management critically important for tropical RAS.

Endemic Diseases:

Tropical regions often serve as endemic habitats for specific shrimp pathogens, including White Spot Syndrome Virus (WSSV), *Vibrio parahaemolyticus* (the causative agent of Acute Hepatopancreatic Necrosis Disease, AHPND) and *Enterocytozoon hepatopenaei* (EHP) [16]. Although

RAS offers enhanced biosecurity, introducing pathogens (e.g., via infected post-larvae) remains possible. The intensive nature of aquaculture environments can facilitate rapid disease propagation if biosecurity management fails. Certain RAS conditions, such as low salinity, have been reported to favor the proliferation of specific pathogens like *Vibrio* spp. [30]. While RAS enhance biosecurity by limiting water exchange [21], the high stocking densities and interconnectedness of the system mean that if a pathogen does gain entry (for instance, through infected post-larvae), it can spread swiftly, potentially leading to catastrophic losses [31]. The complexity of RAS (encompassing power supply, filtration and disinfection) is influenced by numerous factors, each playing a critical role in maintaining optimal conditions for shrimp health. Key environmental parameters such as temperature, salinity, dissolved oxygen and pH must be meticulously controlled to ensure stable RAS operation, as deviations can induce stress and disease in shrimp [32]. The complexity of environment control in the system underscores that RAS biosecurity is contingent upon stringent protocols and robust, reliable system operation.

Salinity Management:

Land based RAS or those utilizing water sources with variable salinity, the management of salinity and ionic balance (particularly the Na: K and Mg: Ca ratios) is crucial for shrimp health and performance, especially at low salinities [20]. An improper ionic balance at low salinities can heighten susceptibility to pathogens, as in some instances, reduced salinity has been shown to increase the virulence of *Vibrio sp*. Pathogens [30]. Furthermore, the cost of artificial sea salt for inland RAS can be substantial [20].

Vulnerability to Weather and Climate Change:

Although RAS offer protection from some climatic impacts (e.g., direct effects of rainfall), extreme weather events can still damage infrastructure such as air and electricity supplies [33]. The durability of water distribution infrastructure is crucial for maintaining the quality and quantity of the water supply for RAS; disruptions caused by aging or fragile water channels and extreme weather events (such as floods and droughts) can damage piping, thereby degrading system performance [34]. Overall, integrating adaptive management strategies, underpinned by comprehensive risk assessments and stakeholder engagement, is essential for enhancing RAS resilience against the threats of weather variability and climate change [35].

Future Perspective of RAS application for the Whiteleg shrimp industry

Enhancing the future viability and competitiveness of RAS requires addressing several key trends and developments. These include the trends towards hybrid systems, such as Biofloc-RAS and Zero Water Discharge-RAS, along with continuous innovations pointed at reducing costs, improving energy efficiency and adapting the technology to specific tropical conditions. Further exploration into the potential of RAS to offer enhanced pliability against the impacts of climate change is also warranted [12].

Addressing existing challenges through research and development could significantly increase shrimp production, improve food security and promote economic development in tropical regions, while also minimizing the environmental footprint associated with traditional aquaculture practices. Recognizing this potential, however, requires a determined commitment from researchers, industry stakeholders and governments. Moreover, this includes focusing on technology innovation, building human resource capacity and establishing supportive policy frameworks that incentivize the adoption of more sustainable aquaculture technologies.

Conclusion

The application of Recirculating Aquaculture Systems (RAS) for vannamei shrimp culture in tropical regions is technically possible, as demonstrated by various pilot-scale trials and commercial implementations. However, its widespread adoption is still limited when compared to the more predominant intensive pond systems. The principal obstacles to mass adoption are the substantial initial investment and ongoing operational costs, as well as the technological complexity, which demands specialized expertise. Despite these challenges, there is a growing interest in RAS, pushed by the demand for sustainable production intensification, improved biosecurity to mitigate disease outbreaks and firmer environmental regulations.

References

1. Tian J, Wu W, Li J, Wan X, Zhao Z, Xi R *et al*. Development Dilemma of *Litopenaeus vannamei* Industry in China, Current Countermeasures Taken and Its Implications for the World Shrimp Aquaculture Industry. Israeli Journal of Aquaculture – Bamidgeh 2023; 76(3). https://doi.org/10.46989/001c.122102.
2. Emerenciano MGC, Miranda-Baeza A, Martínez-Porchas M, Poli MA, Vieira FDN. Biofloc Technology (BFT) in Shrimp Farming: Past and

present shaping the future. Frontiers in Marine Science 2021; 8. https://doi.org/10.3389/fmars.2021.813091.

3. Gutierrez-Perez ED, Vázquez-Juárez R, Magallón-Barajas FJ, Martinez-Mercado M A, Escobar-Zepeda A *et al*. How a holobiome perspective could promote intensification, biosecurity and eco-efficiency in the shrimp aquaculture industry. Frontiers in Marine Science 2022; 9. https://doi.org/10.3389/fmars.2022.975042.
4. Emerenciano MGC, Rombenso AN, Vieira FDN, Martins MA, Coman GJ, Truong HH *et al*. Intensification of Penaeid Shrimp Culture: An Applied Review of Advances in Production Systems, Nutrition and Breeding. Animals 2022; 12(3): 236. https://doi.org/10.3390/ani12030236.
5. Boyd CE, McNevin AA, Racine P, Tinh HQ, Minh HN, Viriyatum R *et al*. Resource Use Assessment of Shrimp, *Litopenaeus vannamei* and *Penaeus monodon*, Production in Thailand and Vietnam. Journal of the World Aquaculture Society 2016; 48(2): 201-226. https://doi.org/10.1111/jwas.12394.
6. Gherman VD, Cimpoiaşu VM, Moga IC, Popa R. Conservation of Aquatic Ecosystems by Constraining Nitrogen Pollution through Aquaculture Effluents. International Journal of Conservation Science 2023; 14(3):1107-1126. https://doi.org/10.36868/ijcs.2023.03.21
7. Ramiro BDO, Wasielesky W, Pimentel OALF, Sun T, McAlhaney E, Urick S *et al*. Assessment of Water Quality, Growth of *Penaeus vannamei* and Partial Budget in Super-Intensive BFT and RAS: A Comparison Between Sustainable Aquaculture Systems. Sustainability 2024; 16(24): 11005. https://doi.org/10.3390/su162411005.
8. Duan Y, Zhong G, Nan Y, Yang Y, Xiao M, Li H. Effects of Nitrite Stress on the Antioxidant, Immunity, Energy Metabolism and Microbial Community Status in the Intestine of *Litopenaeus vannamei*. Antioxidants 2024; 13(11): 1318. https://doi.org/10.3390/antiox13111318.
9. López-Landavery EA, Urquizo-Rosado Á, Saavedra-Flores A, Tapia-Morales S, Fernandino JI, Zelada-Mázmela E. Cellular and transcriptomic response to pathogenic and non-pathogenic *Vibrio parahaemolyticus* strains causing acute hepatopancreatic necrosis disease (AHPND) in *Litopenaeus vannamei*. Fish & Shellfish Immunology

2024; 148: 109472. https://doi.org/10.1016/j.fsi.2024.109472.

10. Yanti H A, Putri DA, Fajriyah SZ. Simulation of a Dissolved Oxygen (DO) Monitoring System in Vannamei Shrimp Aquaculture Based on the Internet of Things (IoT). Journal of Informatics and Communication Technology (JICT) 2023; 5(1):57–67. https://doi.org/10.52661/j_ict.v5i1.156.

11. Xu J, Du Y, Su G, Wang H, Zhang J, Tian H *et al*. Application of a U-Tube Oxygenator in a *Litopenaeus vannamei* Recirculating Aquaculture System: Efficiency and Management Models. Water 2023; 15(22): 4019. https://doi.org/10.3390/w15224019.

12. Shirly-Lim YL, Rahmah S, Ghaffar MA, Liang LQ, Chang YM, Chisti Y *et al*. Pacific whiteleg shrimps compromize their physiological needs to cope with environmental stress. Environmental Advances 2024; 15: 100492. https://doi.org/10.1016/j.envadv.2024.100492.

13. Indian National Fisheries Development Board (NFDB) [Internet]. Establishment of Demonstration Units on Recirculatory Aquaculture Culture Systems for Doubling the Farmers Income in Vannamei Shrimp Culture 2020 [cited 2025 April 22]. Available from: https://nfdb.gov.in/PDF/NFDB-Projects/Final%20report%20of%20Vannamei%20RAS.pdf.

14. Supriyono E, Rasul N, Budiardi T, Hastuti YP, Adiyana K, Thesiana L. A study on the effect of different colours of culture tanks in nursery, on the production performance, biochemical composition of flesh and physiological responses of whiteleg shrimp (*Litopenaeus vannamei*). Aquaculture Research 2021; 52(9): 4086-4093. https://doi.org/10.1111/are.15246.

15. Suantika G, Situmorang ML, Kurniawan JB, Pratiwi SA, Aditiawati P, Astuti DI *et al*. Development of a zero water discharge (ZWD)-Recirculating aquaculture system (RAS) hybrid system for super intensive white shrimp (*Litopenaeus vannamei*) culture under low salinity conditions and its industrial trial in commercial shrimp urban farming in Gresik, East Java, Indonesia. Aquacultural Engineering 2018; 82: 12-24. https://doi.org/10.1016/j.aquaeng.2018.04.002.

16. Panutrakul S, Senanan W. Abundance of introduced Pacific whiteleg shrimp Penaeus vannamei (Boone, 1931) along the east coast of Thailand. Aquatic Invasions 2021; 16(4): 750-770.

https://doi.org/10.3391/ai.2021.16.4.10.

17. Nunes AJP, Coutinho AG, de Sena DC, Rufino LA, Oliveira Neto SC, Neto HS *et al*. Culture of Pacific white shrimp juveniles in super-intensive conditions [Cited 2025 April 25]. Global Seafood Alliance [Internet]. Available from: https://www.globalseafood.org/advocate/culture-of-pacific-white-shrimp-juveniles-in-super-intensive-conditions/.
18. Intriago P., Espinoza J, Cabrera J, Sanchez A, Navarrete A. Nitrogen Flow in a Recirculating Operation of *Litopenaeus vannamei* Maturation in Ecuador. Journal of Aquaculture Research and Development 2012; 3(8):1-8. https://doi.org/10.4172/2155-9546.1000153.
19. Xu W, Xu Y, Su H, Hu X, Yang K, Wen G *et al*. Characteristics of Ammonia Removal and Nitrifying Microbial Communities in a Hybrid Biofloc-RAS for Intensive *Litopenaeus vannamei* Culture: A Pilot-Scale Study. Water 2020; 12(11): 3000. https://doi.org/10.3390/w12113000.
20. Fleckenstein LJ, Tierney TW, Fisk JC, Ray AJ. Using alternative low-cost artificial sea salt mixtures for intensive, indoor shrimp (*Litopenaeus vannamei)* production. Aquaculture Reports. 2022; 24: 101147. https://doi.org/10.1016/j.aqrep.2022.101147.
21. De Lima PCM, Da Silva AEM, Da Silva DA, De Oliveira CYB, Severi W, Brito LO *et al*. Use of recirculation and settling chamber in synbiotic multi-trophic culture of Crassostrea sp. with *Litopenaeus vannamei*. Aquaculture Research 2022; 53(18): 6626-6640. https://doi.org/10.1111/are.16132.
22. Zhao C, Bao G, Mei B, Luo Y, Xu J, Xu S *et al*. Study on the aquaculture capacity of whiteleg shrimp (*Litopenaeus vannamei*)-razor clam (*Sinonovacula constricta*) tandem mariculture pond. Aquaculture Reports 2025; 40: 102625. https://doi.org/10.1016/j.aqrep.2025.102625.
23. Pumkaew M, Taweephitakthai T, Satanwat P, Yocawibun P, Chumtong P, Pungrasmi W *et al*. Use of ozone for *Vibrio parahaemolyticus* inactivation alongside nitrification biofilter treatment in shrimp-rearing recirculating aquaculture system. Journal of Water Process Engineering 2021; 44: 102396. https://doi.org/10.1016/J.JWPE.2021.102396.
24. Teitge F, Peppler C, Steinhagen D, Jung-Schroers V. Water disinfection by ozonation has advantages over UV irradiation in a brackish water recirculation aquaculture system for Pacific white shrimp (*Litopenaeus*

vannamei). Journal of Fish Diseases 2020; 43(10): 1259-1285. https://doi.org/10.1111/JFD.13238.

25. Xu J, Qiu T, Fudi C, Li Z, Jianming S, Du Y. Construction and application of an electrocoagulation and filtration linkage control system in a recirculating aquaculture system. Journal of Water Process Engineering 2021; 44: 102379. https://doi.org/10.1016/J.JWPE.2021.102379.
26. Suantika G, Situmorang ML, Nurfathurahmi A, Taufik I, Aditiawati P, Yusuf N *et al*. Application of Indoor Recirculation Aquaculture System for White Shrimp (*Litopenaeus vannamei*) Growout Super-Intensive Culture at Low Salinity Condition. Journal of Aquaculture Research & Development 2018; 09(04). https://doi.org/10.4172/2155-9546.1000530
27. Costa DP da, Gemaque TC, Pereira LV, Oliveira ADL, Filho KCM. Influence of Annatto (*Bixa orellana*) Extract and Different Shading Levels on *Litopenaeus vannamei* Color Reared Inland Using Biofloc Technology. Journal of Agricultural Studies 2023; 11(1): 22. https://doi.org/10.5296/jas.v11i1.20658.
28. Kir M, Sunar MC, Topuz M, Sarıipek M. Thermal acclimation capacity and standard metabolism of the Pacific white shrimp *Litopenaeus vannamei* (Boone, 1931) at different temperature and salinity combinations. Journal of Thermal Biology 2022; 112: 103429. https://doi.org/10.1016/j.jtherbio.2022.103429.
29. Badiola M, Basurko O, Gabiña G, Mendiola D. Integration of energy audits in the Life Cycle Assessment methodology to improve the environmental performance assessment of Recirculating Aquaculture Systems. Journal of Cleaner Production 2017; 157:155–166. https://doi.org/10.1016/j.jclepro.2017.04.139.
30. Bauer J, Teitge F, Neffe L, Adamek M, Jung A, Peppler C *et al*. Impact of a reduced water salinity on the composition of Vibrio spp. in recirculating aquaculture systems for Pacific white shrimp (*Litopenaeus vannamei*) and its possible risks for shrimp health and food safety. Journal of Fish Diseases. 2020; 44(1):89-105. https://doi.org/10.1111/jfd.13270.
31. Walker PJ, Winton JR. Emerging viral diseases of fish and shrimp. Veterinary Research 2010; 41(6): 51-75. https://doi.org/10.1051/vetres/2010022.
32. Li H, Cui Z, Cui H, Bai Y, Yin Z, Qu K. A review of influencing factors

on a recirculating aquaculture system: Environmental conditions, feeding strategies and disinfection methods. Journal of the World Aquaculture Society 2023; 54(3): 566-602. https://doi.org/10.1111/jwas.12976.

33. Wróbel J, Gałczyńska M, Tański A, Korzelecka-Orkisz A, Formicki K. The challenges of aquaculture in protecting the aquatic ecosystems in the context of climate changes. Journal of Water and Land Development 2023; 57: 231-241. https://doi.org/10.24425/jwld.2023.145354.

34. Tiedmann HR, Faust KM, Sela L. Looking beyond individual failures: A system-wide assessment of water infrastructure resilience to extreme events. Reliability Engineering & System Safety 2024; 244: 109910. https://doi.org/10.1016/j.ress.2023.109910.

35. Masanja F, Luo X, Jiang X, Xu Y, Mkuye R, Zhao L. Environmental and social framework to protect marine bivalves under extreme weather events. Science of the Total Environment 2024; 946: 174471. https://doi.org/10.1016/j.scitotenv.2024.174471.

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CHAPTER

Low Salinity *Litopenaeus vannamei* Aquaponics: Waste Calculation, Plant Role, Density Optimization and Aquaponics Cultivation System

Mat Fahrur
Research Organization for Agriculture and Food, National Research and Innovation Agency. Indonesia. Jl. Raya Jakarta Bogor No.32, Pakansari, Cibinong District, Bogor Regency, West Java 16915, Indonesia.

Rachman Syah*
Research Organization for Agriculture and Food, National Research and Innovation Agency. Indonesia. Jl. Raya Jakarta Bogor No.32, Pakansari, Cibinong District, Bogor Regency, West Java 16915, Indonesia.

Dody Dharmawan Trijuno
Department of Aquaculture, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar, Indonesia.

Zainuddin
Department of Aquaculture, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar, Indonesia

Sahabuddin
Research Organization for Agriculture and Food, National Research and Innovation Agency. Indonesia. Jl. Raya Jakarta Bogor No.32, Pakansari, Cibinong District, Bogor Regency, West Java 16915, Indonesia.

Hidayat Suryanto Suwoyo
Research Organization for Agriculture and Food, National Research and Innovation Agency. Indonesia. Jl. Raya Jakarta Bogor No.32, Pakansari, Cibinong District, Bogor Regency, West Java 16915, Indonesia.

Corresponding Author: rachman.syah@brin.go.id

Abstract

The advantages of *L. vannamei* are in its euryhaline nature, which includes thriving in a wide range of salinity levels, suitability for super-intensive culture densities and relatively high resistance to changes in water quality. A significant challenge associated with super-intensive culture densities is the generation of waste rich in total nitrogen (TN) and total phosphate (TP), causing a potential threat to sustainable shrimp cultivation. Therefore, to produce environmentally friendly shrimp products, there is a need for technology, such as aquaponics between L. vannamei and plants, at low salinity levels. Studies on aquaponics systems at low salinity are important for determining the response of shrimp growth, the potential for TN and TP waste production, as well as the role of plants in absorbing TN and TP in aquaponics systems. Several methods were employed, including recirculation and non-recirculation systems, as well as simple aquaponics. The results of some studies have shown that *L. vannamei* adapted well to low salinity and exhibited normal growth at super-intensive densities. As stocking densities increase, the potential for TN and TP waste accumulation rises, showing the crucial role of plants in absorbing these nutrients and maintaining water quality conducive to shrimp growth.

Keywords: Aquaponics, *L. vannamei*, aquaculture waste, plants, low salinity.

Introduction

An aquaponic system can be used to manage L. vannamei shrimp cultivation waste. This system uses the concentration of TN and TP to meet the needs of plant growth. It reduces the concentrations of N and P in the cultivation medium's water, maintaining water quality. In intensive to superintensive L. vannamei cultivation, the concentration of TN and TP reached 6 mg/L and 1.5 mg/L, respectively [1], It increased from the first week [2]. This is so that the management of nitrogen (N) and phosphorus (P) concentrations continues to be carried out in order to maintain water quality according to the recommended cultivation standards.

Aquaponics is a fish farming system that integrates fisheries and agriculture to mitigate the environmental impact of nutrient waste disposal, which can contribute to environmental eutrophication [3]. Maintaining the cultivation environment is imperative for the generation of uncontaminated water resources and the development of environmentally friendly and sustainable cultivation [4]. The objective is to minimize the environmental impact of aquaculture [5]. maximize the efficiency of clean water usage for every kilogram of shrimp produced [6] and generate higher profits [7]. This approach is intended to facilitate the production of fishery products with minimal environmental impact.

The characteristics of L. vannamei shrimp include living at super high density, utilizing water space effectively and being resistant to changes in water quality, diseases and euryhaline. So shrimp cultivation continues to develop from the sea, brackish to fresh. Cultivated using open and closed systems, recirculation aquaculture systems (RAS) and aquaponics. This is to meet the protein needs and demands of the world market. So, the goal is to reduce environmental impact, produce pesticide-free plants and cultivate is rampant.

Low Salinity Aquaponics

The potential for low salinity aquaponics in Indonesia is quite high due to the tropical nature of the geographical area, with sunlight being an important factor in plants' photosynthesis process. Indonesia, as an archipelagic country with high shrimp production, possesses a significant advantage that can be continuously developed.

L. vannamei is a euryhaline fishery commodity that can live and thrive in low to high salinity. A previous study showed that low salinity does not affect the growth of *L. vannamei* but is influenced by temperature [8]. Moreover, shrimp can live normally at a salinity of 1 ppt when adaptation is carried out properly [9] by adding potassium (K) to water media and increasing survival [10, 11]. Salinity adaptation system is the key to the success of low salinity shrimp cultivation. Stress levels are reduced by maintaining shrimp osmotic to increase survival because hemolymph osmolality decreases with decreasing salinity [12]. However, previous studies on the role of myo-inositol showed the adaptive ability of *L. vannamei* to low salinity [13].

Information on low salinity aquaponics in Indonesia is still lacking. However, low salinity aquaponics between *L. vannamei* and water spinach plants at super-intensive densities with different shrimp densities obtain the best survival and growth at 1,000/m^3. In aquaponics, at super-intensive densities between 1,000-3,000 fish/m^3, the recirculation system using water spinach plants obtains a survival rate of 18.00-55.00% with productivity of 2.51-3.22 kg/m^3 [13a]. A simple system without using a pump for recirculation with different salinities has a significant effect of $P<0.05$ on shrimp growth and survival. According to a previous study, shrimp growth was higher at a salinity of 5 ppt [14a]. *L. vannamei* with intensive density at a salinity of 1 ppt using lettuce plants obtained survival and daily growth rates of 81.33-94.74% and 11.95-13.09%, respectively [15], but there was no information on lettuce plants.

Potential of TN and TP Waste at Low Salinity

Cultivation waste in vannamei shrimp cultivation is a major reason for adopting aquaponics system. Semi-intensive to super-intensive vannamei shrimp produced solid and liquid cultivation waste with high nitrogen (N) and phosphate (P) content [16]. At high salinity, the estimated waste load produced reaches 50.12 gTN/kg shrimp and 15.73 gTP/kg shrimp at a density of 500 shrimp/m^3 [17]. Meanwhile, at low salinity, the recirculation system produced waste reaching 6,57 mg/L TN dan 1,21 mg/L TP [19].

The high and low total nitrogen (TN) and total phosphate (TP) produced by shrimp during cultivation were influenced by the nutritional characteristics of the feed, species and environment [20a, 21-25]. Shrimp feed had a concentration of protein as a source of N, fat, carbohydrates, vitamins and minerals. A portion of feed is wasted and some dissolves into water body and the rest becomes sediment [26]. The uneaten feed undergoes decomposition by bacteria, leading to an increase in the concentration of N and P in water. When this condition is not properly managed, there will be a significant increase in N and P, specifically NH_3, which is toxic. In this condition, the role of plants in aquaponics system becomes crucial, specifically in converting NO_3 into plant biomass through root uptake and photosynthesis facilitated by sunlight [27, 28]. The expectations achieved are shrimp production as a source of protein, plants as a vegetable source and the efficiency of clean water as a preserved natural resource.

Potential of Adaptive Plants to Salinity

In Indonesia, plants that are adaptive to salinity levels in soil media with the addition of salt include tomatoes [29], lettuce dan pak choi [30], water spinach [31], cayenne pepper [32], cowpeas [33] and rice [34-36]. The diversity of plants used as vegetables and main food sources should be explored to increase food production and support national food security. Furthermore, the rich diversity of species in the country is a strength that can be developed. A previous study on salinity stress on plants in soil media included tomatoes, cucumbers, shallots and large red chilies in the category of plants that can adapt, grow and bear fruit [37]. Similarly, water spinach, mustard greens, green beans, corn and peanuts can survive at low salinity levels [38].

Rice plants cultivated in salinity interruption areas with tiger prawns grow and produce grain, known as the 'rice-tiger prawn' system [39]. A study conducted by [40] reported that rice cultivation with giant freshwater prawns increased yields by 68–204 kg/ha. However, the discovery of a method for cultivating rice and shrimp on land with low salinity and acid sulfate soil is an alternative that allows for more productive use of idle land [41], specifically through the integration of rice and tiger prawn [42].

Plants successfully cultivated in low salinity aquaponics systems, including tomatoes and *L. vannamei*, can grow and bear fruit normally at a salinity of 5 ppt [43-45]. Non-fruiting plants (broccoli and cabbage) can produce 4.90–5.05 tons/ha of shrimp when cultivated in aquaponics system with *L. vannamei* [46]. Meanwhile, *Ipomoea aquatica* is able to absorb TN and TP well in low-salinity *L. vannamei* cultivation. Further studies are needed on the potential of plants that are adaptive to salinity stress in *L. vannamei* aquaponics system.

Water Management

Maintaining water sources from pollution and using clean water efficiently is the basis of low salinity aquaponics cultivation [47]. Electrical energy efficiency is also a special concern due to the effect on production costs. Therefore, efforts to reduce the cost of clean water and energy require environmentally friendly cultivation with simple technology [48]. A more environmentally friendly method is through the use of aquaponics system [49].

Low salinity aquaponics is very water-efficient due to the ability to maintain the level of water that evaporates due to evaporation. This is carried out by adding water to cultivation media container every day. The recirculation system is also carried out by pumping cultivation media using a submersible pump to water spinach plant container, as shown in Figure 42. Using this method, TN and TP in water media will be distributed continuously to plant media and spinach plants absorb TN and TP for growth. Water quality parameters, such as NO_2 are below the required threshold, while TAN, NO_3 and PO_4 are greater than cultivation requirement limits. Biofilters in aquaponics system were carried out by plant roots, specifically TSS (Total Suspended Solids), which was automatically filtered and the concentration of N and P was absorbed by the roots into plant biomass [50]. The flow of cultivation water rich in N and P nutrients to plants was generally carried out by flowing water from shrimp cultivation container to the plants [51].

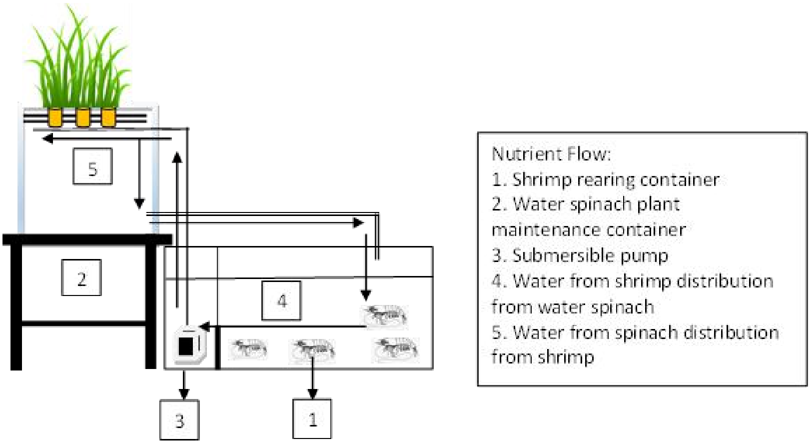

Fig 42: Nutrient flow in low salinity aquaponics *between L. vannamei and* water spinach

Source: [14]

Simple aquaponics combines shrimp and plants in a single cultivation container to reduce costs, land efficiency, electricity and clean water, as shown in Figure 43. A simple system combines pets and plants, making it more efficient in cultivation, land, electricity and clean water [52]. Furthermore, a simple aquaponics system with low salinity, integrating *L. vannamei* and water spinach outdoors can improve water quality by reducing the levels of TAN, NO_2, NO_3 and PO_4. This system used 0.65–0.86 m^3 of water per kilogram of shrimp cultivated [15].

Low Salinity Aquaponics Components

The components used in the recirculation aquaponics system are adjusted according to the technology to be applied. Cultivation containers can be prepared using an outdoor or indoor system. Furthermore, the basic principle in the recirculation system is the use of a submersible pump to circulate water to plant cultivation containers, as shown in Figure 44. A submersible pump circulates the fish cultivation container into the media, enabling consistent nutrient distribution through the maintenance period [53, 54].

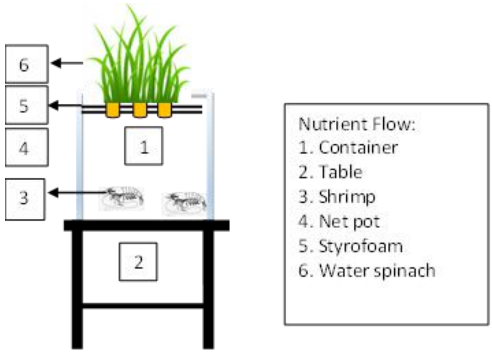

Fig. 393: Simple low salinity aquaponics between L. vannamei and water spinach

Source: Fahrur et al. [15].

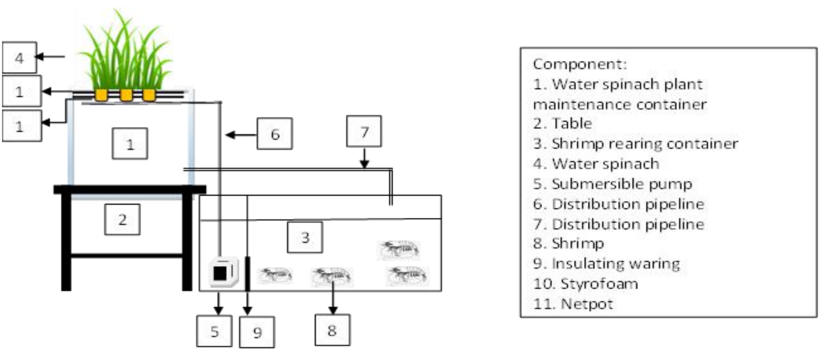

Fig 44: Low salinity aquaponics components between L. vannamei and water spinach

Source: Fahrur et al. [14]

Land Potential

Land optimization is a serious concern for the current government. This is due to the extensive increase in land intruded by seawater due to rising sea levels [55]. In Indonesia, some studies reported that seawater intrusion was increasingly widespread in Makassar [56], Pangandaran [57] and Semarang [58]. Climate change increases seawater intrusion, causing freshwater to become saltier and warmer as saltwater moves further inland [59, 60]. Another study predicted that the area of intruded land will continue to increase [61]. Land affected by seawater intrusion poses a significant risk due to elevated soil salinity, which can lead to plant mortality and land abandonment [62]. As a result, farmers experience losses due to lost income [63] or decreased crop production [64], necessitating efforts to increase land productivity.

Conclusion

Super-intensive cultivation of L. vannamei shrimp at low salinity with water spinach plants can be carried out due to shrimp cultivation waste, which comes from shrimp feed and metabolism. It contains high concentrations of TN (Total Nitrogen) and TP (Total Phosphorus). This waste can be used as nutrients for water spinach plants so that the plants can absorb and utilize nutrients for growth. Thus, water spinach plants act as natural biofilters that help improve water quality during shrimp rearing, maintain nutrient balance and support the survival rate and growth of L. Vannamei shrimp. This approach can also reduce the accumulation of waste that has the potential to pollute the environment, thus creating a more sustainable and efficient ecosystem.

References

1. Lingzi L, Yunmeng L, Yan W. Growth of White Shrimp (*Litopenaeus Vannamei*) and Environmental Variation in Greenhouse Ponds Located in Zhoushan City of Zhejiang Province." Zhejiang Daxue Xuebao (Nongye Yu Shengming Kexue Ban).Journal of the Zhejiang University - Agriculture and Life Science 2020; 46 (4): 489–99. https://doi.org/10.3785/j.issn.1008-9209.2019.08.301.
2. Lien NTK, Kim NT, Tu TPTC, Son VN and Diep DX. Zooplankton Composition in Super-Intensive Whiteleg Shrimp, *Litopenaeus Vannamei* (Boone, 1931) Culture Tanks. Hayati Journal of Biosciences 2022; 29 (6): 851–62. https://doi.org/10.4308/hjb.29.6.851-862.
3. Li J, Yang P, Sohail H, Du H, Li L. The Impact of Short-Term Nitrogen Starvation and Replenishment on the Nitrate Metabolism of Hydroponically Grown Spinach. Scientia Horticulturae 2023;309:111632. https://doi.org/10.1016/j.scienta.2022.111632.
4. Chairat S, Regmi S, Cheng HW, Vongmahadlek P, Gheewala SH. Life Cycle Assessment of Tilapia Production via Conventional Aquaculture and Aquaponic Systems. Aquaculture 2025; 608: 742760. https://doi.org/10.1016/j.aquaculture.2025.742760.
5. Eissa AA, Chen P, Brown PB, Huang JY. Effects of Feed Formula and Farming System on the Environmental Performance of Shrimp Production Chain from a Life Cycle Perspective. Journal of Industrial Ecology 2022; 26 (6): 2006–19. https://doi.org/10.1111/jiec.13370.

6. Rong F, Liu H, Zhu J, Qin G. Carbon Footprint of Shrimp (Litopenaeus Vannamei) Cultured in Recirculating Aquaculture Systems (RAS) in China. Journal of Cleaner Production 2025; 510: 145606. https://doi.org/10.1016/j.jclepro.2025.145606.

7. Yep B, Gale NV, Zheng Y. Comparing Hydroponic and Aquaponic Rootzones on the Growth of Two Drug-Type Cannabis Sativa L. Cultivars during the Flowering Stage. Industrial Crops and Products 2020; 157: 112881. https://doi.org/10.1016/j.indcrop.2020.112881.

8. Sun Z, Lin P, Mai H, Chen L, Wei Z, Tan B *et al*. Metabolomics Profiles Revealed Potential Biomarkers of Pacific White Shrimp (Litopenaeus Vannamei) under Cold and Low Salinity Stress. Aquaculture Reports 2025; 40: 102633. https://doi.org/10.1016/j.aqrep.2025.102633.

9. Jaffer YD, Saraswathy R, Ishfaq M, Antony J, Bundela DS, Sharma PC. Effect of Low Salinity on the Growth and Survival of Juvenile Pacific White Shrimp, *Penaeus Vannamei*: A Revival. Aquaculture 2020; 515: 1–7. https://doi.org/10.1016/j.aquaculture.2019.734561.

10. Widodo AF, Pantjara B, Adhiyudanto NB, Syah S. Performansi Fisiologis Udang Vaname. Jurnal Riset Akuakultur 2011; 6: 225–41.

11. Supono, Pinem RT, Sarida M. The Growth Performance of the Pacific White Shrimp (Litopenaeus Vannamei) Cultured at Various Salinity Conditions Using Single Step Acclimation. AACL Bioflux. 2022; 15 (2): 1061–66.

12. Abrori M, Soegianto A, Winarni D. Survival, Osmoregulatory and Hemocyte Changes in Litopenaeus Vannamei Postlarvae Acclimated to Different Intervals of Salinity Reduction. Aquaculture Reports 2022; 25: 101222. https://doi.org/10.1016/j.aqrep.2022.101222.

13. Lin S, Wu Y, Zhang Z, Wang X, Han F, Xu C *et al*. Myo-Inositol Oxygenase: A Key Player in the Battle of Pacific White Shrimp (Penaeus Vannamei) against Low-Salinity Stress. Aquaculture Reports. 2025; 42: 102788. https://doi.org/10.1016/j.aqrep.2025.102788.

14. Fahrur F, Trijuno DD, Zainuddin, Syah R. Waste Estimation and Increased Production of Water Spinach (*Ipomoea Reptans Poir* Sp) in Low Salinity Vannamei Shrimp Aquaponics Cultivation. IOP Conference Series: Earth and Environmental Science 2024; 1400 (1). https://doi.org/10.1088/1755-1315/1400/1/012010.

15. Fahrur M, Trijuno DD, Zainuddin, Undu MC, Makmur, Taukhid I *et al*. A study on aquaponic cultivation vannamei shrimp (Litopenaeus Vannamei) and water spinach (Ipomoea Aquatica Forsk) under low salinity. Indonesian Aquaculture Journal. 2024; 19 (1): 57–73. https://doi.org/10.15578/iaj.19.1.2024.57-73.
16. Hermawan D. Aplication of Aquaponics Technology for Pasific White Shrimp Litopenaeus Vannamei in Low Salinity with Lattuce at the Different Stocking Density." Jurnal Ilmu Pertanian Dan Perikanan 2015; 4 (1): 79–85.
17. Suwoyo HS, Tuwo A, Haryati, Anshary H. Potential, Characteristics and Utilization of Shrimp Pond Solid Waste as Organic Fertilizer. International Journal of Environment, Agriculture and Biotechnology 2019; 4 (2): 411–21. https://doi.org/10.22161/ijeab/4.2.24.
18. Syah R, Makmur, Undu MC. Estimasi Beban Limbah Nutrien Pakan Dan Daya Dukung Kawasan Pesisir Untuk Tambak Udang Vaname Superintensif. Jurnal Riset Akuakultur 2014; 9 (3): 439. https://doi.org/10.15578/jra.9.3.2014.439-448.
19. Alarcón-Silvas SG, León-Cañedo JA, Fierro-Sañudo JF, Ramirez-Rochin J, Fregoso-Lopez MG, Frias-Especueta MG *et al*. Water Quality, Water Usage, Nutrient Use Efficiency and Growth of Shrimp Litopenaeus Vannamei in an Integrated Aquaponic System with Basil *Ocimum Basilicum*. Aquaculture 2021; 543. https://doi.org/10.1016/j.aquaculture.2021.737023.
20. Rodríguez-Olague D, Ponce-Palafox JT, Castillo-Vargasmachuca SG, Arámbul-Muñoz E, Santos RCDL, Esparza-Leal HM. Effect of Nursery System and Stocking Density to Produce Juveniles of Whiteleg Shrimp *Litopenaeus Vannamei*. Aquaculture Reports 2021; 20. https://doi.org/10.1016/j.aqrep.2021.100709.
21. Hopkins JS, Hamilton RD, Sandier PA, Browdy CL, Stokes AD. Effect of Water Exchange Rate on Production, Water Quality, Effluent Characteristics and Nitrogen Budgets of Intensive Shrimp Ponds. Journal of the World Aquaculture Society 1993; 24 (3): 304–20. https://doi.org/10.1111/j.1749-7345.1993.tb00162.x.
22. Silva KRD, Wasielesky WJr, Abreu PC. Nitrogen and Phosphorus Dynamics in the Biofloc Production of the Pacific White Shrimp, *Litopenaeus Vannamei*. Journal of the World Aquaculture Society 2013; https://doi.org/10.1111/jwas.12009.

23. Xu J, Wang F, Hu C, Lai J, Xie S, Yu K *et al*. Dietary High Plant Protein and High Lipid Impaired the Intestine Health of Grouper by Disrupting Oxidative Stress, Immune Response and Protein Metabolism. Aquaculture Reports 2024; 39: 102389. https://doi.org/10.1016/j.aqrep.2024.102389.

24. Chen K, Li E, Xu C, Wang X, Li H, Qin JG *et al*. Growth and Metabolomic Responses of Pacific White Shrimp (*Litopenaeus Vannamei*) to Different Dietary Fatty Acid Sources and Salinity Levels. Aquaculture 2019; 499: 329–40. https://doi.org/10.1016/j.aquaculture.2018.09.056.

25. Tian J, Xu Q, Liu J, Luo M, Hu W, Tian L *et al*. Optimal Dietary Protein Level for the White Shrimp (*Litopenaeus Vannamei*) in Low Salinity Water. Israeli Journal of Aquaculture – Bamidgeh. 2016; 68. https://doi.org/10.46989/001c.20798.

26. Paena M, Syamsuddin R, Rani C, Tandipayuk H. Estimation of the Burden of Organic Waste from Superintensive Shrimp Ponds Wasted in the Waters of Labuange Bay. Jurnal Ilmu Dan Teknologi Kelautan Tropis 2020; 12 (2): 509–18. https://doi.org/10.29244/jitkt.v12i2.27738.

27. Forchino AAH, Lourguioui, Brigolin D and Pastres R. Aquaponics and Sustainability: The Comparison of Two Different Aquaponic Techniques Using the Life Cycle Assessment (LCA). Aquacultural Engineering 2017; 77: 80–88. https://doi.org/10.1016/j.aquaeng.2017.03.002.

28. Pérez-Urrestarazu L, Lobillo-Eguíba J, Fernández-Cañero R, Fernández-Cabanás VM. Food Safety Concerns in Urban Aquaponic Production: Nitrate Contents in Leafy Vegetables. Urban Forestry and Urban Greening 2019; 44 (May): 126431. https://doi.org/10.1016/j.ufug.2019.126431.

29. Boboy W. Pertumbuhan Dan Hasil Tiga Tanaman Tomat Pada Cekaman Salinitas. Jurnal Partner 2011; 19 (1): 92–101.

30. Susanti M. Pengaruh kadar NaCl dan dosis kompos jerami terhadap pertumbuhan dan hasil tanaman selada (*Lactuca Sativa* L) pada media pasir pantai. Program Studi Agroteknologi. Fakultas Pertanian. Universitas Muhamadiyah Yogyakarta. Skripsi. 2017; 1-14.

31. Rochmania A. Uji Toleransi Salinitas (NaCl) Terhadap Pertumbuhan, Kadar Klorofil, Dan Prolin Tiga Varietas Kangkung Darat (*Ipomoea*

Reptans Poir). Islam Negeri Maulana Malik Ibrahim, Malang. Skripsi. 2021;1-147.

32. Bastomi MY. Efek Cekaman Salinitas (NaCl) Terhadap Pertumbuhan Dua Varietas Cabai Rawit (*Capsicum Frutescens* L.). Jurusan Biiologi. Fakultas Sains dan Teknologi. Univertisa Negeri (UIN) Maulana Malik ibrahim. Malang. 2018; Skripsi. 5-115.
33. Junandi, Mukarlina, Linda R. Pengaruh Cekaman Salinitas Garam NaCl Terhadap Pertumbuhan Kacang Tunggak (*Vigna Unguiculata* L. Walp) Pada Tanah Gambut. Jurnal Protobiont 2019; 8 (3): 101–5. https://doi.org/10.26418/protobiont.v8i3.36869.
34. Nasruddin, Isnaeni S. Tercekam Salinitas Dengan Umur Bibit Berbeda. Jurnal Ilmiah Pertanian. Universitas Yudharta Pasuruan. Agromix 2022; 13 (1): 118–25.
35. Saragih, Setyowati BWM, Nanik, Nurjanah P, Uswatun. Optimasi Lahan Pada Sistem Tumpang Sari Jagung Manis. Jurnal Agroqua 17 (2): 115–25. https://doi.org/10.32663/ja.v.
36. Taufiq A, Kristiono A and Harnowo D. Respon Varietas Unggul Kacang Tanah Terhadap Cekaman Salinitas. Jurnal Penelitian Pertanian Tanaman Pangan 2019; 34 (2): 153–64.
37. Yamika WSD, Aini N and Setiawan A. Penentuan Batas Toleransi Salinitas Beberapa Tanaman (Tomat, Mentimun, Bawang Merah Dan Cabai Besar) Pada Cekaman Salinitas. Prosiding Seminar Nasional Pembangunan Pertanian 2016; 35–40.
38. Sihotang T. Pengaruh Cekaman Salinitas Terhadap Pertumbuhan Tanaman Semusim. Fruitset Sains : Jurnal Pertanian Agroteknologi. 2021; 9 (2): 45–51.
39. Sahabuddin, Cahyadi A, Nafisah N, Suwoyo HS, Nawang A, Septiningsih E *et al*. The Utilization of Brackish Water-Induced Land through a Rice-Tiger Shrimp Coculture System. Aquaculture Reports. 2024; 34: 101909. https://doi.org/10.1016/j.aqrep.2023.101909.
40. Bhowmik BC, Rima NN, Gosh K, Hossain MDA, Murray FJ, Little DC *et al*. Salinity Extrusion and Resilience of Coastal Aquaculture to the Climatic Changes in the Southwest Region of Bangladesh. Heliyon. 2023; 9 (3): e13935. https://doi.org/10.1016/j.heliyon.2023.e13935.
41. Ngoc NP, Dang LV, Qui NV, Hung NN. Chemical Processes and Sustainability of Rice-Shrimp Farming on Saline Acid Sulfate Soils in

Mekong Delta. Heliyon 2023; 9 (2): e13532. https://doi.org/10.1016/j.heliyon.2023.e13532.

42. Leigh C, Stewart-Koster B, Sang NV, Truc LV, Sammut J, Burford MA. Rice-Shrimp Ecosystems in the Mekong Delta: Linking Water Quality, Shrimp and Their Natural Food Sources. Science of the Total Environment 2020; 739: 139931. https://doi.org/10.1016/j.scitotenv.2020.139931.

43. Fierro-Sanudo JF, Alarcon-Silvas SG, Leon-Canedo JG, Gutierrez-Valenzuela JG, Ramirez-Rochin J, Franco-Nava MA *et al*. Integrated Culture of Shrimp (*Litopenaeus vannamei*), Tomato (*Lycopersicon esculentum*) and Lettuce (*Lactuca sativa*) Using Diluted Seawater : Management, Production and Water Consumption. Global Advanced Research Journal of Agricultural Science 2015; 4 (7): 315–24. http://garj.org/garjas/home.

44. Goddek S, Joyce A, Wuertz S, Körner O, Bläser I, Reuter M, Keesman KJ. Decoupled Aquaponics Systems. Aquaponics Food Production Systems 2019; https://doi.org/10.1007/978-3-030-15943-6_8.

45. Armenta-Bojórquez AD, Valenzuela-Castañeda AR, Fitzsimmons K, Lopez-Alvarez ES, Rodriguez-Quiroz G. Pacific White Shrimp and Tomato Production Using Water Effluents and Salinity-Tolerant Grafted Plants in an Integrated Aquaponic Production System. Journal of Cleaner Production. 2021; 278. https://doi.org/10.1016/j.jclepro.2020.124064.

46. Ni M, Yuan J, Hua J, Lian Q, Guo A, Liu M *et al*. Shrimp–Vegetable Rotational Farming System: An Innovation of Shrimp Aquaculture in the Tidal Flat Ponds of Hangzhou Bay, China. Aquaculture. 2020; 518: 734864. https://doi.org/10.1016/j.aquaculture.2019.734864.

47. Horta-Puga G. Environmental Impacts. Coral Reefs of the Southern Gulf of Mexico. 2007 126–41. https://doi.org/10.4337/9781788975391.00008.

48. Fefilova E, Dubovskaya O, Frolova L, Abramova E, Kononova O, Nigamatzyanova G *et al*. Biogeographic Patterns of Planktonic and Meiobenthic Fauna Diversity in Inland Waters of the Russian Arctic. Freshwater Biology. 2022; 67 (1): 78–94. https://doi.org/10.1111/fwb.13624.

49. Rodrigues AB, Pinheiro IC, Nonato TCM, Ferenhof EA, Sens ML. Valorization of Reverse Osmosis Concentrate in the Production of *Litopenaeus vannamei* and New Zealand Spinach in an Aquaponic

System with Biofloc. Desalination. 2023; 549: 116330. https://doi.org/10.1016/j.desal.2022.116330.

50. Lastiri DR. Modelling and Identification of Water and Nutrient Balances in Aquaponics. Wagening University, the Netherlands. 2021;Thesis. 5-156.
51. Suantika G, Situmorang ML, Kurniawan JB, Pratiwi SA, Aditiawati P, Astuti DI *et al*. Development of a Zero Water Discharge (ZWD)—Recirculating Aquaculture System (RAS) Hybrid System for Super Intensive White Shrimp (*Litopenaeus vannamei*) Culture under Low Salinity Conditions and Its Industrial Trial in Commercial Shrimp Urban Farming in Gresik, East Java, Indonesia. Aquacultural Engineering. 2018; 82: 12–24. https://doi.org/10.1016/j.aquaeng.2018.04.002.
52. Saha S, Monroe A, Day MR. Growth, Yield, Plant Quality and Nutrition of Basil (*Ocimum Basilicum* L.) under Soilless Agricultural Systems. Annals of Agricultural Sciences. 2016; 61 (2): 181–86. https://doi.org/10.1016/j.aoas.2016.10.001.
53. Munawarawanti AE, Omar SBA, Syamsuddin R, Syaiful SA, Ulfa F, Dachlan A. The Effectiveness of Biofilter and Density of Different Stocking in Aquaponic Resirculation Systems in the Integration of Tilapia (*Oreochromis niloticus* L.) and Pakchoy Plants (*Brassica rapa* L.). IOP Conference Series: Earth and Environmental Science. 2020; 486 (1). https://doi.org/10.1088/1755-1315/486/1/012137.
54. Bordignon F, Birolo M, Fanizza C, Trocino A, Zardinoni G, Stevanato P *et al*. Effects of Water Salinity in an Aquaponic System with Rainbow Trout (*Oncorhynchus mykiss*), Black Bullhead Catfish (*Ameiurus melas*), Swiss Chard (*Beta vulgaris*) and Cherry Tomato (*Solanum lycopersicum*). Aquaculture. 2024; 584. https://doi.org/10.1016/j.aquaculture.2024.740634.
55. Pietkiewicz H, Mortimer RJG, Hirst AG, Lewis JP, Clarke L, Little S. Artificial Barriers and Estuarine Squeeze: A Novel Assessment of Estuarine Vulnerability to Climate Change and Sea Level Rise. Estuarine, Coastal and Shelf Science 2025; 320. https://doi.org/10.1016/j.ecss.2025.109299.
56. Mas'ud L, Azikin B, Umar H, Zubair H. Delineation of Seawater Intrusion, Using Geo-Electric Resistivity Method, in Shallow Aquifer in Western Part of Makassar, South Sulawesi, Indonesia. Iraqi Geological

Journal 2024; 57 (2): 109–23. https://doi.org/10.46717/igj.57.2D.9ms-2024-10-19.

57. Yuliatmoko RS, Kurniawan T, Sunardi B, Hardy T, Martha AA, Rohadi S *et al*. Case Study: Estimating the Occurrence of Sea Water Intrusion Using Geoelectrical Method in Pangandaran District. IOP Conference Series: Earth and Environmental Science 2021; 708 (1). https://doi.org/10.1088/1755-1315/708/1/012002.
58. Setyawan A, Najib, Ariwibowo Y, Trihadini A, Hastuti D, Ramdhani F *et al*. Sea Water Intrusion in Kaligawe Semarang Based on Resistivity Data Preface: International Conference on Recent Trends in Physics (ICRTP 2016). International Conference Series on Tropical and Coastal Region Eco Development. 2016; 55.012053. https://doi.org/ 10.1088/1755-1315/55/1/012053.
59. Kaushal SS, Shelton SA, Mayer PM, Kellmayer B, Utz RM, Reimer JE *et al*. Freshwater Faces a Warmer and Saltier Future from Headwaters to Coasts: Climate Risks, Saltwater Intrusion and Biogeochemical Chain Reactions. Biogeochemistry 2025; Vol. 168. Springer International Publishing. https://doi.org/10.1007/s10533-025-01219-6.
60. Akter R, Hasan N, Reza F, Asaduzzaman MD, Begum K, Shammi M. Hydrobiology of Saline Agriculture Ecosystem: A Review of Scenario Change in South-West Region of Bangladesh. Hydrobiology 2023; 2 (1): 162–80. https://doi.org/10.3390/hydrobiology2010011.
61. He B, Ding J, Huang W, Ma X. Spatiotemporal Variation and Future Predictions of Soil Salinization in the Werigan–Kuqa River Delta Oasis of China. Sustainability 2023;15 (18). https://doi.org/10.3390/su151813996.
62. Tran DQ, Le KN, Durand-Morat A, Nguyen NNT, Bairagi SK, Huynh MVT *et al*. Is It Worth It? Land-Fallowing and Saltwater Intrusion Control under Uncertainty. Science of the Total Environment. 2025; 966: 178711. https://doi.org/10.1016/j.scitotenv.2025.178711.
63. Sembiring H, Erythrina E, Pramudia A, Subekti NA, Nugraha D, Priatmojo B *et al*. Impact of Different Water Management and Microbe Application on Yield of Rice Cultivars under Seawater Intrusion Areas of Indonesia. Chilean Journal of Agricultural Research 2023; 83 (5): 510–24. https://doi.org/10.4067/S0718-58392023000500510.

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CHAPTER

Opportunities and Challenges in the Development of RAS Systems: Social, Economic and Business Model Perspectives

Dendy Mahabror
Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia

Riza Zulkarnain*
Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia

Suhardi Atmoko Budi Susilo
Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia

Asmanik
Research Center for Mariculture, National Research and Innovation Agency (BRIN), Indonesia

Irwan Jatmiko
Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia

Corresponding Author: riza009@brin.go.id

Abstract

Recirculating Aquaculture System (RAS) technology has emerged as a significant advancement in contemporary fish farming, aimed at addressing food security and environmental degradation issues. By utilizing the concepts of water circulation and purification, RAS enhances resource efficiency while producing high-quality, contaminant-free fish products suitable for export. This article analyzes the social and economic dimensions of the RAS system, focusing on its role in enhancing food security, creating jobs and its integration into an integrated farming system within an ideal strategy for developing a business model. This essay analyzes the potential of domestic and global markets as well as the barriers to the implementation of RAS technology related to sustainability and the formation of inclusive business models. This study indicates that the integration of contemporary RAS technology with digital advancements and a circular economy framework will lead to the development of a highly promising Sustainable Business Model (SBM), allowing RAS to function as a fundamental component in the advancement of resilient and sustainable fish farming systems.

Keywords: Recirculating Aquaculture System (RAS), socio-economy, food security, circular economy, business model

Introduction

As the global demand for sustainable animal protein sources increases, recirculating aquaculture system (RAS) technology has become an innovative solution in modern fish farming. RAS allows for the repeated use of water through filtration and purification processes, thereby increasing resource efficiency, minimizing waste and reducing the risk of environmental pollution [1]. With strict environmental control, this system maintains optimal water quality and reduces the risk of fish diseases, making it suitable for implementation in urban areas and regions with limited land. In addition to ecological benefits, RAS also supports circular economy practices and offers opportunities for integration with digital technology and aquaponics to enhance production efficiency sustainably.

In addition to environmental benefits, RAS significantly contributes to social and economic aspects, including food security improvement, community empowerment and income source diversification, especially in rural and urban areas. This system is capable of producing high-quality fish that meet domestic and international food safety standards, opening access to premium markets. Therefore, a deep understanding of socio-economic potential, operational cost efficiency, sustainable business opportunities and market development challenges is crucial to supporting the expansion of RAS as part of fisheries development that is adaptive to climate change and oriented toward sustainability.

Social Aspects in Fish Farming with Recirculating Aquaculture Systems

Nutrition and Job Livelihoods

Land-based fish farming, especially primarily through systems like Recirculating Aquaculture Systems (RAS), plays an important role in improving nutrition and livelihoods for millions of people around the world. RAS enables sustainable fish production with minimal environmental impact by reusing water and providing a controlled environment that supports high-density fish farming. This innovative approach is highly significant for urban areas where land and water resources are limited. Thus, it contributes to food accessibility and nutrition provision, serving as a reliable source of protein amid growing health concerns related to malnutrition faced by urban populations in developing countries [2]. Additionally, its ability to be a long-term solution for food security positions aquaculture as part of a larger system of integrated agriculture, encouraging mutual benefits among different farming methods.

As shown in Table 5, several aquaculture technologies that incorporate inland fisheries into integrated farming systems have proven to enhance resilience to climate change and socio-economic shocks. This practice includes the integration of fish farming with crop and livestock production, thereby optimizing resource use, increasing land efficiency and diversifying agricultural outputs [10]. This approach helps farmers reduce dependence on a single commodity, strengthen their economic sustainability and enhance community resilience to market fluctuations and environmental conditions [11].

Furthermore, inland fisheries play a vital role in providing nutritious protein while supporting the economic stability of local communities. Involvement in traditional fishing and modern fish farming increases income, strengthens food security and meets the nutritional needs of the community [12, 13]. Inland fisheries also serve as an important safety net in low-income areas, especially during times of food crisis or economic instability [14]. Overall, the integration of fisheries into agricultural systems demonstrates strategic potential in strengthening food security and economic resilience for vulnerable communities globally.

Table 5: Integration Models of Agriculture and Aquaculture across Different Regions

Integration Model	Description	Location/Country	Reference
IAA (Integrated Agriculture-Aquaculture)	Integration of fish farming with plants and livestock: utilization of organic waste as feed or fertilizer	Asia and Africa	[3]
Aquaponics	Combination of aquaculture and hydroponics: fish waste as nutrition for plants	Global	[4]
Mina Padi	Fish ponds in the rice fields: fish control pests and fertilize the rice plants	Southeast Asia	[5]
Fish & Poultry Farming	Livestock waste is used as fertilizer for fish ponds	China, Vietnam, Africa	[6]
Reuse Nutrient System	Solid agricultural and livestock waste is used for aquaculture and aquaculture waste is reused as fertilizer.	USA	[7]
Coastal Aquaculture	Integration of coastal ponds	Hawai	[8]

and Agriculture System	with agriculture through nutrient flow and tides		
Integration of Horticulture and Household Aquaculture	Fish farming with home gardens using pond water waste	Nigeria	[9]

Community Welfare

Sustainable aquaculture practices, such as RAS, can enhance community welfare by creating job opportunities and promoting economic stability in rural areas. Sustainable aquaculture practices, such as Recirculating Aquaculture Systems (RAS), are transforming rural economies by creating job opportunities and promoting economic stability. RAS is an innovative method in fish farming that recycles water, thereby reducing environmental impact and increasing efficiency. This technology is capable of meeting local protein demand and minimizing the risks associated with conventional aquaculture practices, positioning itself as a cornerstone for rural livelihoods.

Table 6 indicates that various technological approaches in modern aquaculture, including Biofloc technology, Recirculating Aquaculture System (RAS) and IoT-based monitoring, have significantly improved fish product quality and increased farmers' income. Biofloc technology improves water quality, supports nutrient recycling and strengthens fish immunity, which results in increased harvest yields and reduced feed costs [15]. RAS produces high-quality, contaminant-free fish, opens up export market opportunities and optimizes the use of water and space [16].

Meanwhile, implementing an IoT-based monitoring system supports real-time water condition management, reduces fish mortality rates and minimizes losses [17]. Better feed and breeding management also drives productivity with an optimal feed conversion ratio [18]. Integrating aquaculture with agriculture (IAA) increases profitability by two to three times compared to monoculture systems [19]. The practice of modern feeding and stocking, along with farmer capacity-building programs, significantly increases income and production efficiency [20, 21]. Overall, this technological innovation shows great potential in building a more productive, sustainable and economically profitable aquaculture system.

Table 6: Impact of Aquaculture Technologies on Product Quality and Farmer Income

Technology/Approach	Impact on Product Quality	Impact on Farmer Income	References
Biofloc Technology	Improve water quality, nutrient recycling enhance fish immunity	Increasing yield per unit area reduces feed costs	[15]
RAS Recirculation aquaculture system	Produce high-quality, contaminant-free fish	Suitable for export, reduce water and space costs	[16]
IoT-based monitoring system	Maintenance of optimal water conditions real-time risk alert	Reduce mortality, enhance growth rate and minimize losses	[17]
Improve feed and Hatchery management.	Ensures faster and uniform growth and better feed conversion ratio	Boost productivity and reduce input wastage	[18]
Integrated fish farming (IAA)	Water nutrient balance reduces disease outbreak	Increase profitability by 2-3 times compared to monoculture	[19]
Modern stocking and feeding practice	Enhance survival and growth uniformity	Improve net income and reduce production cycle duration	[20]
Extension and capacity-building programs	Promotes best practice and biosecurity	This leads to a times increase in income in rural aquaculture setting	[21]

Specifically, the Recirculating Aquaculture System (RAS) technology significantly contributes to job creation, income diversification and improving the welfare of communities dependent on aquatic resources [22, 23]. By encouraging the transition from traditional aquaculture practices to technology-based techniques such as RAS, rural communities gain opportunities for better food security and local economic strengthening. Implementing RAS also equips communities with new skills in sustainable fish farming and water quality management, strengthening their adaptive capacity to climate and market changes.

Improvement of Food Security

Fish production through the Recirculating Aquaculture System (RAS) allows for stricter control of water and feed quality control, resulting in healthier and contaminant-free fish products, thereby strengthening food security and increasing public trust in domestic fishery products. Aquaculture, which is now the fastest-growing sector in the animal food production of animal food, plays a crucial role in reducing malnutrition and poverty and creating jobs, especially in developing countries [24]. The use of water-saving technologies such as RAS supports sustainable development goals with the potential to become the most sustainable animal protein production system, though. However, there are still challenges in managing the loss of carbon, nitrogen and phosphorus to the environment [25].

With RAS, water quality management becomes more effective, reducing the need for antibiotics and improving fish health through more sterile and controlled farming conditions [26]. In addition, waste from aquaculture systems, particularly from fish fed with alternative protein-based feed, can be utilized as sustainable fertilizer for hydroponic farming, supporting resource efficiency and the application of circular economy principles [27].

Economic Aspects of Fish Farming with Recirculating Aquaculture Systems

Cost Efficiency and Long-Term Benefits

Although the initial investment in recirculation systems is higher compared to conventional methods, the efficiency in water and feed usage, as well as the reduction in waste management costs, can increase long-term profits. Farmers can also optimize production yields with a more controlled and stable system.

First, in conventional methods, water is usually continuously circulated without considering recycling, which results in significant waste and leads to resource wastage. RAS allows for better waste management, making the system more sustainable and contributing positively to the environment [28]. This feature is very important in the current global context, where reducing water consumption and environmental impact is becoming increasingly urgent.

The use of RAS also provides long-term operational cost savings through feed efficiency. This system allows for more precise adjustments in feed provision, thereby reducing the excessive feeding that often occurs with conventional methods, which are at risk of generating excess waste. Research shows that life cycle analysis between feed, fish production, waste and energy are the main components explaining the ecological impact of RAS. Recent developments in RAS show two trends focused on (1) technical improvements in the recirculation loop and (2) nutrient recycling through integrated farming. Both trends contribute to improving RAS environmental sustainability [29].

Lastly, reducing waste management costs in recirculating systems is another important factor contributing to long-term profitability in aquaculture.

In RAS systems, fish waste and feed residues can be managed more efficiently with the use of additional technologies such as ozonation, biological filtration and nitrification biofiltration, enhancing the efficiency of waste treatment in RAS to recycle water and reduce the accumulation of harmful substances in aquaculture ponds [30]. With the ability to manage waste effectively, farmers not only avoid high costs for waste disposal but also gain the opportunity to utilize waste components from the RAS system as nutrients for plants in aquaponic systems. The overall results indicate that RAS is not just a new technological trend in aquaculture but a practical and sustainable solution that can provide long-term economic benefits for farmers, particularly by enhancing profit potential through integrating aquaculture and agriculture.

RAS is conventionally generally adopted for integrated fish-plant production in aquaponic systems. A study by [31] comparing the economic feasibility of integrated agri-aquaculture production of juvenile tilapia and lettuce in FLOCponics (FP) and conventional Aquaponics (AP) systems produced results as shown in the table below.

The outcomes of fictitious simulations on the traditional aquaponic system (AP) with a success rate of marketable plants at 100% are displayed by FLOCponic and Aquaponic based on the economic data in Table 7. Overall, both situations show that investing in integrated aquaponic systems is highly feasible financially.

The system at FLOCponic produces a Net Present Value (NPV) of USD 48,682.60 and an Internal Rate of Return (IRR) of 22.93%. The discounted payback term is 5.67 years, whereas the payback period is 5.01 years. In the long run, more than one dollar in value is returned for every dollar invested, according to the Benefit-Cost Ratio (BCR) of 1.17 and the Discounted BCR of 1.12.

Table 7: Economic indicators of the different scenarios (FLOCponic vs Aquaponic)

Parameter	FLOCponic	Aquaponic
IRR (%)	22,93	24,67
NPV (US$)	48.682,6	54.483,2
Payback (years)	5,01	4,80
Discounted Payback (years)	5,67	5,38
Benefit/Cost Ratio	1,17	1,18
Discounted Benefit	1,12	1,14

Meanwhile, Aquaponics shows slightly better economic performance, with an IRR of 24.67% and an NPV of USD 54,483.20. The payback period is also faster, at 4.80 years and the discounted Payback is 5.38 years. A BCR of 1.18 and a Discounted BCR of 1.14 further strengthen the argument that this investment is highly economically viable. Overall, both scenarios show that the conventional aquaponic system with a 100% crop yield success rate offers attractive profit potential and is worth recommending as a sustainable agribusiness strategy, especially in the integrated agriculture sector.

Increase in Fish Production and Quality

The Recirculating Aquaculture System (RAS) allows for high-density fish production without causing water quality degradation, creating a more stable environment that directly enhances fish growth and reduces mortality rates [32]. Optimal farming conditions in RAS increase yields and produce fish of better quality, which ultimately enhances the competitiveness of the products in the market. Research by [33] shows that European catfish raised in RAS have better meat quality and healthier blood and serum profiles than fish from earthen ponds. These findings show that improved waste management and water recycling in RAS greatly help fish health and product quality, strengthening modern aquaculture's ability to meet consumer demand for high-quality fish products.

Table 8 shows the growth performance parameters of European catfish comprising first weight, final weight, weight gain, condition factor, visceral somatic index (VSI) and hepatosomatic index (HSI). Except for VSI and HSI, no statistically significant changes were found between fish raised in earthen ponds and fish grown in a recirculating aquaculture system (RAS). The parameters were rather different. Higher yields in the RAS system could follow from fish grown with RAS showing better weight gain (1232g) than fish grown in ponds (1150g).

Table 8: Growth parameters of European catfish from the recirculating aquaculture system and earthen pond

System	IBW (g)	FBW (g)	WG (g)	CF	VSI	HSI	Survival Rate
RAS	174.38±16.34	2233.5±101.61	1232.09±73.31	0.72±0.03	6.49±0.57	2.69±0.19	100
Earthen Pond	212.05±10.42	2598.1±141.89	1150.95±86.99	0.76±0.03	4.55±0.35	2.04±0.12	100
Independent-test	0.68	0.51	0.485	-	0.009	0.011	1
Mann-Whitney	-	-	-	0.143	-	-	-

IBW-initial body weight; FGW-final body weight; WG-weight gain; CF-condition factor; VSI-viscero somatic index; HIS-hepatosomatic index. n=20

The proximate composition of fresh European catfish meat is shown in

Table 9. Compared to fish raised in clay ponds, fish raised in RAS have a significantly higher fat content and a significantly lower moisture and ash content in their fresh meat. However, there were no discernible variations in the protein, collagen or salt characteristics.

Table 9: Proximate composition of European catfish fresh from the recirculating aquaculture system and earthen pond

System	Fat (%)	Moisture (%)	Protein	Collagen	Salt	Ash
RAS	14.08±1.64	68.63±1.15	16.86±0.21	0.38±0.08	0.26±0.10	1.99±0.14
Earthen Pond	7.11±0.90	71.86±0.64	16.63±0.20	0.34±0.07	0.54±0.14	2.58±0.10
Independent-test	0.001	0.020	0.436	-	-	0.001
Mann-Whitney	-	-	-	0.979	0.232	-

Thus, the RAS system not only increases crop yields but also provides a competitive advantage for farmers. When the quality of the fish improves and the mortality rate decreases, the final product becomes more attractive to consumers, which in turn enhances competitiveness in the market.

Market and Export Potential

With the increasing demand for healthy and high-quality fish, fish farming with a recirculating system has a great opportunity to meet the needs of both domestic and international markets. Better food safety standards allow fish products from this system to more easily penetrate the export market, especially in countries with strict regulations on fishery products.

- **Domestic Market**

The domestic demand for high-quality fish drives the need for cultivation systems that can maintain food safety standards, which are challenging to meet by conventional aquaculture due to limited environmental control and contamination risks. Recirculating Aquaculture System (RAS) offers an innovative solution with complete water circulation management, allowing for strict control over water quality, fish density and biosecurity, thereby producing premium fish products that meet the needs of the hotel, restaurant and supermarket markets [34]. In addition to producing healthy and uniform fish, integrating Aquaponics in RAS strengthens the sustainability of local food production, supports "in-sourcing" practices and opens up opportunities for creating new jobs in the technology-based food sector.

Economically, the viability of RAS shows variation depending on the fish species, local market conditions and operational efficiency. A study in Vietnam shows that using RAS in catfish farming increases the net present value to USD 916,000/ha for large enterprises, with an investment success rate of 99%

for medium and large scales [18]. However, economic success still depends on cost management and production yield improvement. Studies in Northern Germany also show that the cultivation of African catfish in RAS has the potential to be profitable through product diversification and further processing [34]. Thus, RAS offers strong prospects for developing sustainable and premium market-oriented fish farming.

- **Export Market**

Countries with strict food safety regulations, such as the European Union, Japan and the United States, become potential export targets for aquaculture products using the Recirculating Aquaculture System (RAS) because this technology allows complete control over water quality, feed and environment, resulting in products that meet international standards such as HACCP, EU Minimum Performance Levels and the Japanese Food Safety Basic Law [35]. RAS effectively reduces the risk of microbial contamination, heavy metals and antibiotic residues, which are the leading causes of rejection of fishery products in the global market, especially in the European Union, through the RASFF system [35]. In Japan, The Application of Closed System Technology (CRAS) enhances the competitiveness of fish products by maintaining freshness, colour and texture according to consumer preferences that highly value quality [36].

Studies in the European Union show that fish products from RAS are considered more environmentally friendly and meet high food safety standards, encouraging consumers to pay a premium price for sustainable products [37]. Similarly, in the United States, species such as golden shiner and pike-perch are cultivated using RAS to ensure year-round production with minimal disease risk and environmental pollution [38]. Thus, implementing RAS enhances the fishery product exports' competitiveness in the global premium market but also supports the fulfillment of increasingly stringent international sustainability and food safety standards.

Table 10 shows the top 10 countries of origin where most received notifications related to product quality, starting with Spain (998 cases, 14.66%), followed by Vietnam (524 cases, 7.70%), Morocco (364 cases, 5.35%), China (305 cases, 4.48%), Indonesia (274 cases, 4.02%), France (259 cases, 3.80%), Denmark (244 cases, 3.58%), Poland (223 cases, 3.28%), the Netherlands (216 cases, 3.17%) and Thailand (185 cases, 2.72%). As much as 52.76% of all notifications come from these countries, with the remaining 47.24% divided among various countries. Previous research has shown that

7.5% of the notified Spanish products originate from America (mainly Mexico, Ecuador and Brazil) and Asia (42%) [39]. Furthermore, Morocco, Ecuador, China, Argentina and India were the leading suppliers in Southern Europe in 2018 [40]. Moreover, most of the hazardous products recorded in the RASFF come from Asian countries [41].

Table 10: Top 10 origin countries involved in RASFF notifications on fish from 2000 to 2022

Country	%	Country	%	Country	%	Country	%	Country	%	Country	%
Spain	14.66	Spain	21.16	Spain	35.94	Poland	23.39	Spain	17.05	Spain	35.41
Vietnam	7.70	Indonesia	10.05	Indonesia	7.26	Denmark	15.00	France	14.43	Portugal	11.67
Morocco	5.35	Vietnam	6.97	Vietnam	6.99	Germany	7.86	Morocco	9.84	Namibia	7.00
China	4.48	Sri Lanka	6.97	Singapore	6.89	United Kingdom	5.54	Norway	8.52	Vietnam	4.67
Indonesia	4.02	Thailand	6.26	Sri Lanka	5.51	France	5.36	Denmark	6.89	Panama	3.89
France	3.80	Netherlands	4.23	Chile	5.24	Norway	5.36	Netherlands	4.92	China	2.72
Denmark	3.58	Ecuador	3.70	Portugal	5.06	United States	4.64	China	4.26	France	2.72
Poland	3.28	Seychelles	3.09	France	3.95	Chile	4.11	Thailand	3.93	Italy	2.33
Netherlands	3.17	Senegal	2.65	Netherlands	2.30	Spain	3.93	Poland	3.28	Morocco	2.33
Thailand	2.72	India	2.12	Denmark	1.84	Netherlands	3.75	Croatia	2.95	Taiwan	2.33
Total	**52.76**	**Total**	**67.20**	**Total**	**80.97**	**Total**	**78.93**	**Total**	**76.07**	**Total**	**75.10**

Opportunities for Developing Fish Farming with Recirculating Aquaculture Systems

Integration with Digital Technology

The integration of digital technology with recirculating aquaculture systems (RAS) holds very promising prospects for enhancing the efficiency and productivity of fish farming. Here are the explanations and findings from several studies:

- **Sensors and automation enhance water quality monitoring**

The Internet of Things (IoT) in aquaculture systems depends on the progress of information and communication technologies; thus, they become essential. IoT solutions in this system use the interconnectivity among devices to gather fish pond monitoring data from sensor devices and send that data to a remote server for analysis in pond management decision-making. This enables farmers to track the health situation of fish from several ponds, control fish production cycles, record fish feeding schedules and monitor sensor readings [42].

- **Feed automation increases cost efficiency and fish growth**

The automatic feeding system integrated with fish growth and behaviour data can reduce waste and optimize feed conversion [43]. State that the automated system can improve feed efficiency, enhance fish growth through scheduled feed management and maintaining water quality and reduce reliance on manual labour. However, this system also has challenges, such as the need for a significant initial investment, dependence on system supplies and the necessity for regular device maintenance. This technology provides a promising modern system to enhance efficiency and productivity in small to medium-scale fish farming.

- **Artificial intelligence (AI) for action-taking and early disease detection**

AI predicts growth, detects diseases early and automatically adjusts environmental parameters. This helps optimize production and reduce dependence on the subjective experience of the cultivators. The study by [44] on using machine learning with the Gradient Boosting Algorithm model, one of the most popular machine learning algorithms for prediction and classification, works by gradually building predictive models (stepwise and iterative). By using a dataset from various parameters such as pH, DO, BOD, COD, TSS, TDS, EC, PO_4^{3-}, NO_3-N and NH_3-N as input for calculating the final WQI (Water Quality Index) value will be used for classifying water status and as input in the machine learning model to detect fish diseases. Early detection is important because it allows for prevention before mass fish deaths occur, significantly improving aquaculture yields.

Diversification of Fish Species

Species diversification in global aquaculture shows a continuously developing positive trend, with an increasing number of species cultivated in various regions worldwide. Although most production is still concentrated on a small number of main species, there is an increasing contribution from non-traditional species in many countries. Countries with high production capacity and supportive policies are showing greater diversification. This diversification is important to enhance food and economic resilience and reduce biological and market risks from dependence on species. However, challenges remain, including infrastructure, technology, markets and policies supporting new species' cultivation. Therefore, a more coordinated and policy-based approach is needed to promote sustainable diversification in aquaculture [45].

Figure 45 shows the growth of aquaculture species diversity from 1950 to 2015, where the number of species increased significantly from around 600 to

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about 1,800. The blue line on the graph reflects a stable trend in species richness, while the green bars show fluctuations in the annual growth rate of species diversity, which have tended to increase particularly in recent years. This indicates that although species richness has increased, the annual growth rate has experienced variability, likely due to changes in aquaculture management practices and environmental factors. Calculating the Annual Growth Rate (AGR) during that period, approximately 3.42% was obtained, indicating the average annual growth of aquaculture species [46]. This graph highlights the long-term increase in aquaculture species diversity and reflects positive progress in fisheries management to enhance biodiversity.

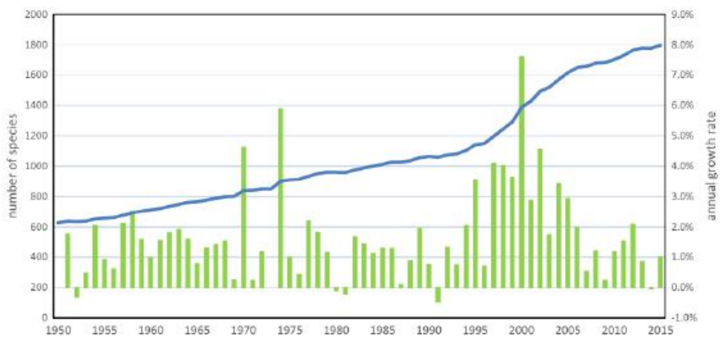

Fig 45: Fishery species diversity (species richness and annual growth rate)

Sustainable Business Model (SBM)

Fish farming using the Recirculating Aquaculture System (RAS) offers broad, flexible and sustainable business prospects, both on a small scale and industrial scale. On a small scale, RAS allows for fish farming management in limited areas with high water use efficiency and environmental quality control, supporting local food security. On the industrial side, RAS enables intensive fish production in a closed system that produces high-quality, contamination-free and export-worthy products. In addition to fish, RAS also supports business diversification by utilizing solid waste as organic fertilizer and the potential for agro-tourism. Although challenges such as high initial capital requirements, energy dependence and technical expertise pose obstacles, the opportunity to meet the local and global market demand for sustainable protein remains significant. With support from training, digital technology and public and private sector incentives, RAS can become an inclusive, efficient and environmentally friendly future aquaculture solution.

Therefore, to see the prospects and challenges of the Sustainable Business Model (SBM) from this RAS system, the author approached it with a TOWS analysis. According [47], TOWS is an extension of the SWOT (Strengths, Weaknesses, Opportunities, Threats) method, which is used to formulate strategies based on the relationship between internal factors (strengths and weaknesses) and external factors (opportunities and threats). The main objective is to help organizations optimize strengths and opportunities, as well as minimize weaknesses and threats through concrete and structured strategies.

The TOWS analysis matrix (Table 11) indicates that fish farming technology utilising the Recirculating Aquaculture System (RAS) formulates strategies that leverage internal strengths, including water efficiency, product quality and environmental control, to seize opportunities in the high-quality fish market and export demand. Aggressive strategies (SO) promote the incorporation of technology like AIoT and the diversification of products, such as organic fertiliser and agrotourism. Simultaneously, the WO strategy emphasises enhanced human resource capabilities and improved access to funding, particularly for MSME stakeholders. Defensive measures (WT and ST) promote the adoption of small-scale systems, the utilisation of renewable energy and market education to enhance acceptance of RAS technology.

Table 11: TOWS Matrix Strategy Sustainable Business Model RAS System

SO (Aggressive) • Utilize RAS efficiency for the high-end export market; • Provide eco-friendly products; • Integrate AIoT for competitiveness and efficiency; • Diversify your product line to include organic fertilizers and agro-tourism.	**WO (Conservative)** • Utilize government incentives and capacity building; • Development of small-scale household RAS; • Digital training for farmers; • Cooperative and incubator partnership.
ST (Competitive) • High levels of biosecurity to prevent disease; • effectiveness to endure changes in the market; • and branding of iconic and sustainable products.	**WT (Defensive)** • Starting on a small scale to minimize risk; • The use of renewable energy for efficiency; • Building a community of RAS users; • Market education to reduce technology resistance.

Conclusion

The Recirculating Aquaculture System (RAS) offers innovative and sustainable fish farming solutions that can address global food security challenges, land limitations and the need for high-quality fishery products. This study shows that RAS provides efficient use of resources such as water and feed and generates significant social and economic impacts, including increased community income, job creation and integration into integrated agriculture. Better fish quality, high biosecurity control and significant export potential are added values of this technology. On the other hand, implementing RAS also faces challenges, such as high initial costs and the need for technical expertise. However, with policy support, digital innovation and sustainable business models, RAS can be adopted from household scale to large industries. Therefore, RAS can potentially become a key pillar in developing resilient, efficient and environmentally friendly aquaculture systems in the future.

References

1 Prama EA, Kurniaji A. Performa pertumbuhan dan kualitas air pada pendederan lobster pasir *Panulirus homarus* yang dipelihara dengan sistem resirkulasi. J Ilmu Dan Teknologi Kelautan Tropis 2022;14:259–72. https://doi.org/10.29244/jitkt.v14i2.37116.

2 Benjamin EO, Ola O, Buchenrieder GR. Feasibility study of a small-scale recirculating aquaculture system for sustainable (Peri-)urban farming in sub-saharan africa: a nigerian perspective. Land 2022;11:2063. https://doi.org/10.3390/land11112063.

3 Prein M. Integration of aquaculture into crop–animal systems in Asia. Agricultural Systems 2002;71:127–46. https://doi.org/10.1016/S0308-521X(01)00040-3.

4 Zajdband AD. Integrated agri-aquaculture systems. In: Lichtfouse E, editor. Genetics, Biofuels and Local Farming Systems. Dordrecht: Springer Netherlands 2011;7:87–127. https://doi.org/10.1007/978-94-007-1521-9_4.

5 Sugunan VV, Prein M, Dey MM. Integrating Agriculture Fisheries Ecosystem Conservation Win-win Solutions. International Journal of Ecology and Environmental Sciences 2006; 32; 1:3–14.

6 Brummett RE, Jamu DM. From researcher to farmer: partnerships in

integrated aquaculture—agriculture systems in Malawi and Cameroon. International Journal of Agricultural Sustainability 2011;9:282–9. https://doi.org/10.3763/ijas.2010.0570.

7 A. M. Lazur AM, Leteux F. Integrated aquaculture systems for nutrient reduction in agricultural wastewater: potential and challenges. Bull. Fish. Res. Agen. Supplement 2004;1:143–151.

8 Farrant DN, Frank KL, Larsen AE. Reuse and recycle: Integrating aquaculture and agricultural systems to increase production and reduce nutrient pollution. Science of The Total Environment 2021;785:146859. https://doi.org/10.1016/j.scitotenv.2021.146859.

9 Olukunle OJ, Omotoso JA. Nutritive potential of sweet potato peel meal and replacement value for maize in the diet of African catfish (*Clarias gariepinus*) fingerlings. Journal of Agricultural Science 2014;5;5:134–141. https:// doi.org/10.5539/jas.v5n5p134.

10 Paramesh V, Ravisankar N, Behera U, Arunachalam V, Kumar P, Solomon Rajkumar R *et al*. Integrated farming system approaches to achieve food and nutritional security for enhancing profitability, employment and climate resilience in India. Food and Energy Security 2022;11:e321. https://doi.org/10.1002/fes3.321.

11. Rathnachandra SDD, Malkanthi SHP. Socio-Economic Importance of Inland Fishery and Adaptive Strategies of Inland Fishermen at Udawalawe Reservoir, Sri Lanka. SL J Soc Sci Hum 2024;4:37–49. https://doi.org/10.4038/sljssh.v4i2.123.

12. Simmance FA, Simmance AB, Kolding J, Schreckenberg K, Tompkins E, Poppy G *et al*. A photovoice assessment for illuminating the role of inland fisheries to livelihoods and the local challenges experienced through the lens of fishers in a climate-driven lake of Malawi. Ambio 2022;51:700–15. https://doi.org/10.1007/s13280-021-01583-1.

13 Moreau MA, Garaway CJ. Fish Rescue us from Hunger: the Contribution of Aquatic Resources to Household Food Security on the Rufiji River Floodplain, Tanzania, East Africa. Hum Ecol 2018;46:831–48. https://doi.org/10.1007/s10745-018-0030-y.

14 Lammers PL, Richter T, Mantilla-Contreras J. From Safety Net to Point of No Return—Are Small-Scale Inland Fisheries Reaching Their Limits? Sustainability 2020;12:7299. https://doi.org/10.3390/su12187299.

15 Auwalu J. Emerging trends: The rise of biofloc fish farming in modern aquaculture. Proceedings of the 49th Conference of the Nigerian Society for Animal Production. Ibadan, Nigeria 2024 ; March 24–27:1930–1932.

16 Clough S, Mamo J, Hoevenaars K, Bardocz T, Petersen P, Rosendorf P *et al*. Innovative Technologies to Promote Sustainable Recirculating Aquaculture in Eastern Africa—A Case Study of a Nile Tilapia (*Oreochromis niloticus*) Hatchery in Kisumu, Kenya. Integrated Environmental Assessment and Management 2020; 16:934–41. https://doi.org/10.1002/ieam.4295.

17 Florestiyanto MY, Ashrianto PD, Yuwono B, Himawan H. Evaluation of Usage Behaviour of IOT-Based Aquaculture Technologies. Proceeding of LPPM UPN “VETERAN” Yogyakarta Conference Series 2020- Political and Social Science Series, Rsf Press & Research Synergy Foundation 2020: 248–56. https://doi.org/10.31098/pss.v1i1.202.

18 Ngoc PTA, Meuwissen MPM, Cong Tru L, Bosma RH, Verreth J, Lansink AO. Economic feasibility of recirculating aquaculture systems in pangasius farming. Aquaculture Economics & Management 2016; 20:185–200. https://doi.org/10.1080/13657305.2016.1156190.

19 Chandra G, Kumar Chaudhary P, Kumar M. Integrated fish farming system: a way towards sustainability and prosperity of farmers. EEC 2023; 29:432–4. https://doi.org/10.53550/EEC.2023.v29i03s.074.

20 Sakib MH and Afrad MSI. Adoption of modern aquaculture technologies by the fish farmers in Bogra district of Bangladesh. International Journal of Agriculture Innovations and Research 2014; 3;2:414–421. https://www.researchgate.net/publication/277535477 (Accessed: February 2025)

21 Msiska OV, UJahengo TP, Domenica LD, Mshalie M, Mussa H, Mlenga I *et al*. Innovative Extension Services for Technology Transfer: The Case of Aquaculture in Northern Malawi. EJFST 2024; 12:36–53. https://doi.org/10.37745/ejfst.2013/vol12n23653.

22 Van Huong N, Huu Cuong T, Thi Nang Thu T, Lebailly P. Efficiency of Different Integrated Agriculture Aquaculture Systems in the Red River Delta of Vietnam. Sustainability 2018; 10:493. https://doi.org/10.3390/su10020493.

23 Diedrich A, Blythe J, Petersen E, Euriga E, Fatchiya A, Shimada T *et al*.

Socio-economic drivers of adoption of small-scale aquaculture in Indonesia. Sustainability 2019; 11(6):1543. doi: 10.3390/su11061543.

24 Khanjani MH, Sharifinia M, Hajirezaee S. Strategies for promoting sustainable aquaculture in arid and semi-arid areas – A review. Annals of Animal Science 2024; 24(2):293–305. doi: 10.2478/aoas-2023-0073.

25 Prüter J, Strauch SM, Wenzel LC, Klysubun W, Palm HW, Leinweber P. Organic matter composition and phosphorus speciation of solid waste from an African catfish recirculating aquaculture system. Agriculture 2020;10(10):466. doi: 10.3390/agriculture10100466.

26 Boyd CE, D'Abramo LR, Glencross BD, Huyben DC, Juarez LM, Lockwood GS *et al*. Achieving sustainable aquaculture: Historical and current perspectives and future needs and challenges. Journal of the World Aquaculture Society 2020; 51(3):578–633. doi: 10.1111/jwas.12714.

27 Jones JJ, Shaw C, Chen T, Staß CM, Ulrichs C, Riewe D et al. Plant nutritional value of aquaculture water produced by feeding Nile tilapia (*Oreochromis niloticus*) alternative protein diets: A lettuce and basil case study. Plants, People, Planet 2024;6(2):362–380. doi: 10.1002/ppp3.10457.

28 Gonçalves Junior LP, Lara BS, Carvalho SAD, Leal CAG, Miranda Filho KC, Figueiredo HCP *et al*. Ultraviolet radiation and water salinization on recirculating aquaculture systems. Pesquisa Agropecuária Brasileira 2020; 55:e01804. doi: 10.1590/S1678-3921.pab2020.v55.01804.

29 Martins CIM, Eding EH, Verdegem MCJ, Heinsbroek LTN, Schneider O, Blancheton JP *et al*. New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. Aquacultural Engineering 2010; 43(3):83–93. doi: 10.1016/j.aquaeng.2010.09.002.

30 Mongirdas V, Žibienė G, Žibas A. Waste and its characterization in closed recirculating aquaculture systems – a review. Journal of Water Security 2017; 3(1). doi: 10.15544/jws.2017.002.

31 Pinho SM, Flores RMV, David LH, Emerenciano MGC, Quagrainie KK, Portella MC. Economic comparison between conventional aquaponics and FLOCponics systems. Aquaculture 2022;552:737987. doi: 10.1016/j.aquaculture.2022.737.

32 Kamali S, Ward VCA, Ricardez-Sandoval L. Dynamic modeling of

recirculating aquaculture systems: Effect of management strategies and water quality parameters on fish performance. Aquacultural Engineering 2022; 99:102294. doi: 10.1016/j.aquaeng.2022.102294.

33 Barbacariu CA, Rimbu CM, Burducea M, Dirvariu L, Miron LD, Boiangiu RS *et al*. Comparative study of flesh quality, blood profile, antioxidant status and intestinal microbiota of European catfish (*Silurus glanis*) cultivated in a recirculating aquaculture system (RAS) and earthen pond system. Life 2023; 13(6):1282. doi: 10.3390/life13061282.

34 Lal J, Vaishnav A, Deb S, Kashyap S, Debbarma P, Devati P *et al*. Recirculatory aquaculture systems: A pathway to sustainable fish farming. Archives of Current Research International 2024; 24(5):799–810. doi: 10.9734/acri/2024/v24i5756.

35 Nguyen AVT, Wilson LW. Effects of food safety standards on seafood exports to US, EU and Japan. AgEcon Research in Agricultural and Applied Economics 2009.

36 Eissa F, Younes A. Fish contamination: Analysis of the EU RASFF notifications over the last 23 years. Food Control 2024; 161:110404. doi: 10.1016/j.foodcont.2024.110404.

37 Takeuchi T. Overview of land-based recirculating aquaculture. In: Takeuchi T, editor. Application of Recirculating Aquaculture Systems in Japan. Springer Japan 2017. p. 3–18. doi: 10.1007/978-4-431-56585-7_1.

38 Tye M. Methods for rearing golden shiner fry in a recirculating aquaculture system. North American Journal of Aquaculture 2013; 75(1):39–41. doi: 10.1080/15222055.2012.713893.

39 D'Amico P, Nucera D, Guardone L, Mariotti M, Nuvoloni R, Armani A. Seafood products notifications in the EU Rapid Alert System for Food and Feed (RASFF) database: Data analysis during the period 2011–2015. Food Control 2018;93:241–250. doi: 10.1016/j.foodcont.2018.06.018.

40 Caldeira AJR, Alves CPP, Santos MJ. Anisakis notification in fish: An assessment of the cases reported in the European Union Rapid Alert System for Food and Feed (RASFF) database. Food Control 2021;124:107913. doi: 10.1016/j.foodcont.2021.107913.

41 Pigłowski M. Food hazards on the European union market: The data analysis of the rapid alert system for food and feed. Food Science and Nutrition 2020; 8(3):1603–1627. doi: 10.1002/fsn3.1448.

42 Darmalim F, Hidayat AA, Cenggoro TW, Purwandari K, Darmalim S, Pardamean B. An integrated system of mobile application and IoT solution for pond monitoring. IOP Conference Series: Earth and Environmental Science 2021; 794(1):012106. doi: 10.1088/1755-1315/794/1/012106.

43 Zuriati Z, Supriyatna AR, Arifin O. Design and development of feeding automation system and water quality monitoring on freshwater fish cultivation. IOP Conference Series: Earth and Environmental Science 2022;1012(1):012077. doi: 10.1088/1755-1315/1012/1/012077.

44 Nayan AA, Saha J, Mozumder AN, Mahmud KR, Al Azad AK, Kibria MG. A machine learning approach for early detection of fish diseases by analyzing water quality. Trends in Sciences 2021; 18(21):351. doi: 10.48048/tis.2021.351.

45 Cai J, Chan HL, Yan X, Leung P. A global assessment of species diversification in aquaculture. Aquaculture 2023; 576:739837. doi: 10.1016/j.aquaculture.2023.739837.

46 Sicuro B. World aquaculture diversity: Origins and perspectives. Reviews in Aquaculture 2021; 13(3):1619–1634. doi: 10.1111/raq.12537.

47 Dimitrova TV, Desev K. Strategic analysis through the combination of SWOT, AHP and TOWS (A case study on the neurological ward in the MHAT 'Saint Panteleymon' – Plovdiv). Economic Studies journal, Bulgarian Academy of Sciences - Economic Research Institute 2018;issue 3:67–90.

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CHAPTER

Circular Economy in Recirculating Aquaculture Systems (RAS): Maximizing Resource Utilization

Bambang Gunadi
Research Center for Freshwater Aquaculture, National for Research and Innovation Agency (BRIN), Indonesia

Idil Ardi*
Research Center for Freshwater Aquaculture, National for Research and Innovation Agency (BRIN), Indonesia

Lies Setijaningsih
Research Center for Freshwater Aquaculture, National for Research and Innovation Agency (BRIN), Indonesia

Wahyu Pamungkas
Research Center for Freshwater Aquaculture, National for Research and Innovation Agency (BRIN), Indonesia

Dewi Puspaningsih
Research Center for Freshwater Aquaculture, National for Research and Innovation Agency (BRIN), Indonesia

Tutik Kadarini
Research Center for Freshwater Aquaculture, National for Research and Innovation Agency (BRIN), Indonesia

Corresponding Author: ardiidil02@gmail.com

Abstract

Recirculating Aquaculture Systems (RAS) provides a sustainable alternative to traditional aquaculture by reducing water use and waste. However, adoption in tropical smallholder settings like Indonesia faces challenges, including high costs, technical complexity and limited infrastructure. This paper explores integrating circular economy principles into RAS to enhance efficiency, resilience and livelihoods for rural communities. It emphasizes low-tech, affordable strategies tailored to tropical climates, such as repurposing treated water, nutrients and solid waste into valuable products like microalgae, microbial biomass, organic fertilizers and biogas. These approaches leverage Indonesia's climate to accelerate biological processes while ensuring system stability. The study highlights resource optimization, low-cost methods like gravity-based recirculation and composting and community-driven processing models. Circular RAS reduces operational costs, creates jobs, diversifies income and strengthens food security. However, barriers like capital constraints, knowledge gaps and weak policies persist. By proposing scalable, inclusive solutions, this study positions circular RAS as a transformative model for sustainable aquaculture in Southeast Asia, aligning with climate adaptation and rural development goals. It offers practical guidance for researchers, policymakers and farmers to drive innovation and adoption of circular practices in tropical aquaculture.

Keywords: Recirculating Aquaculture Systems (RAS), circular economy, microalga production, biofertilizer, tropical aquaculture, resource valorization, waste repurposing.

Introduction

Aquaculture is a rapidly growing food production sector, essential for global food security and livelihoods, particularly in tropical and developing regions like Indonesia, the world's second-largest aquaculture producer [1]. However, traditional pond-based systems face challenges from declining natural resources, water scarcity, land use conflicts and environmental degradation [2]. Recirculating Aquaculture Systems (RAS) address these issues by providing controlled, water-efficient and biosecure environments, recycling up to 99% of water through treatment processes [3]. Despite these benefits, high operational costs and management complexities in tropical climates pose sustainability and economic barriers [4, 5].

The circular economy (CE) offers a framework to overcome these challenges by minimizing waste, optimizing resources and repurposing materials. CE promotes regenerative systems where outputs become inputs for other processes, reducing environmental impact [6–8]. It operates at micro (individual businesses), meso (eco-industrial parks) and macro (entire economies) levels [9]. CE also emphasizes sustainable business models that reject the traditional end-of-life approach [10, 11]. While integrated multi-trophic aquaculture (IMTA), aquaponics and biofloc systems are common CE applications in aquaculture [12], non-aquaponics CE strategies in RAS, particularly in tropical Southeast Asia, remain underexplored [13].

The practical, low-tech methods to repurpose treated water, dissolved nutrients and solid by-products in RAS, will enhance economic resilience and reduce environmental footprints for smallholder farmers in Indonesia. Facing pressure to increase production amid resource constraints and regulatory demands, Indonesia's smallholder-dominated sector struggles with high-tech RAS adoption due to costs and expertise barriers [14, 15]. Low-cost, scalable CE strategies, such as microalgae feed production, biofertilizers and community-based waste management, reduce reliance on external inputs, create revenue streams and generate jobs. These efforts align with United Nations Sustainable Development Goals (SDGs) for Zero Hunger (SDG 2), Clean Water and Sanitation (SDG 6), Responsible Consumption and Production (SDG 12) and Life below Water (SDG 14) [16, 17].

This paper synthesizes recent research and context-specific challenges to position RAS with CE strategies as a scalable model for sustainable aquaculture in Southeast Asia. It focuses on non-aquaponics, non-IoT applications tailored for tropical smallholder systems and outlines: (i) key treated resources in RAS; (ii) methods for internal optimization of water, nutrients and energy; (iii) value-adding applications for treated outputs; (iv) economic and social benefits of circular models; (v) barriers and practical solutions for implementation; and (vi) future directions for scaling these practices across Indonesia and beyond.

Treated Resources for Circular Applications

Recirculating Aquaculture Systems (RAS) are designed to sustain water quality and fish health by continuously treating and reusing water in a near-closed-loop environment. This process generates valuable by-products, e.g. clarified water from filtration, dissolved nutrients (primarily nitrogen compounds) and solid organic waste from uneaten feed, fish waste and microbial biomass. Previously regarded as waste, these by-products now offer valuable opportunities within a circular economy (CE) framework to enhance sustainability, operational efficiency and profitability [4, 5].

RAS generates treated water, nutrients (e.g., nitrates, phosphates) and solid wastes (e.g., uneaten feed, feces, microbial flocs) that can be repurposed beyond aquaponics for applications like microalgae cultivation, microbial biomass production, soil amendments and organic fertilizers [18, 19]. These practices lower costs, improve nutrient management and diversify income. In Indonesia's rural aquaculture sector, where advanced technologies and centralized waste management are often inaccessible, low-tech, decentralized solutions are critical for sustainability and economic viability [16]. In warm, tropical climates, accelerated biological processes further increase the potential for resource recovery and reuse, strengthening the resilience and sustainability of decentralized aquaculture operations.

Treated Water: Characteristics and Reuse Potential

As the primary product in RAS, treated water undergoes mechanical, biological and occasionally chemical treatment to maintain optimal conditions. Mechanical filtration removes solids, while biofiltration converts toxic ammonia (NH_3) and nitrite (NO_2^-) into less harmful nitrate (NO_3^-). Additional treatments like UV sterilization, ozone application or degassing further improve water quality [20, 21]. With water reuse rates between 90–99%, RAS dramatically reduce freshwater demand compared to flow-through systems [5].

Beyond reuse within the system, nutrient-rich treated water supports microalgae cultivation for fish feed, biofertilizers and biofuels [22, 23]. Safe, pathogen-free water also serves for irrigation and ornamental plant cultivation [24] or for growing lower trophic aquaculture species like molluscs [25]. In Indonesia's tropical climate, high temperatures and sunlight accelerate microbial metabolism, enhancing nutrient removal and boosting biomass production potential [26]. However, these benefits require careful monitoring of dissolved oxygen, pH and nutrient concentrations to maintain system stability and maximize secondary use opportunities.

Dissolved Nutrients: Composition and Valorization Opportunities

Biofiltration in RAS transforms ammonia and nitrite into nitrate while accumulating phosphates, trace minerals and dissolved organic carbon (DOC) in treated water. If unmanaged, these dissolved nutrients destabilize systems, yet under a CE framework, they represent valuable resources for biomass production and organic fertilizer inputs [18, 27].

Nitrate- and phosphate-rich water supports rapid microalgae growth, yielding high-value biomass from species such as *Chlorella vulgaris*, *Scenedesmus obliquus* and *Nannochloropsis* sp. for aquafeeds, biofertilizers and biofuels [28, 29]. Similarly, dissolved nutrients foster the growth of heterotrophic bacteria like *Bacillus* sp. and *Lactobacillus* sp., producing microbial biomass for probiotics, biofertilizers and organic waste digesters that benefit both aquaculture and agriculture [30]. Nitrate-rich water also serves as a base for liquid biofertilizers, offering an organic alternative to synthetic fertilizers [1]. Careful monitoring is essential to prevent nutrient overaccumulation or losses through volatilization or denitrification, ensuring system stability [30, 31].

In tropical Southeast Asia, rising demand for organic fertilizers and natural feed additives, driven by ecological concerns and high agricultural input costs, makes these valorization strategies particularly promising.

Solid By-Products: Composition and Reuse Pathways

Solid wastes from RAS include uneaten feed, fish feces, microbial flocs and biofilm debris, traditionally discarded but increasingly recognized for their reuse potential [32–34]. Low-tech processing methods like sun drying, composting or anaerobic digestion convert these materials into organic fertilizers, protein-rich aquafeed ingredients and biogas for farm use

Mechanical filtration (settling tanks, drum filters) and foam fractionation efficiently remove solids to maintain water quality. Once separated, solids can be stabilized through dewatering, composting or fermentation. Dried fish waste, rich in nitrogen, phosphorus and organic matter, improves soil fertility as a compost additive or organic soil conditioner [35]. Composting RAS solids reduces farmers' disposal costs while supporting local nutrient cycling and sustainable crop production.

Processed RAS solids can also produce polyhydroxyalkanoates (PHA) and single-cell protein (SCP), valuable as aquafeed additives and immunostimulants [36]. Anaerobic digestion transforms organic solids into methane-rich biogas and nutrient-rich digestate for liquid fertilizers [37].

The treated resources produced within RAS, including clarified water, dissolved nutrients and solid by-products, possess significant potential for circular reuse applications beyond conventional aquaponics. Community-based processing units with shared drying racks, composting pits or biogas digesters offer smallholders cost-effective, scalable options to manage waste valorization collaboratively.

Internal Resource Optimization in RAS

The efficiency and sustainability of Recirculating Aquaculture Systems (RAS) depend on effectively managing and reusing water, nutrients and energy within the system. In low-tech, smallholder aquaculture settings like those in Indonesia, simple, cost-effective strategies are essential for operational viability and environmental sustainability. RAS minimize freshwater use and effluent discharge by continuously treating and recycling water in a closed-loop system. Optimizing the reuse of treated water, dissolved nutrients and by-products reduces waste, lowers costs and enhances environmental performance. In tropical climates, where high temperatures accelerate biological processes, low-tech solutions—such as manual water quality monitoring, gravity-based filtration and passive energy-saving techniques—are well-suited for smallholder and community-based operations, ensuring resource circularity and system resilience [16, 38].

Water Recirculation: Strategies for High-Efficiency Reuse

A hallmark of Recirculating Aquaculture Systems (RAS) is their ability to recycle 90–99% of water daily, maintaining quality for fish health while significantly reducing freshwater use and wastewater discharge compared to traditional pond-based aquaculture [27, 39-41]. In low-tech tropical systems, this is achieved through mechanical filtration, biofiltration and disinfection methods like UV sterilization or ozone application [42, 43].

In tropical settings like Indonesia, elevated temperatures boost evaporation, oxygen demand and waste decomposition, complicating water management [16]. To maintain high recirculation rates affordably, several strategies prove effective. Low-tech water treatment options, such as sand filtration, gravel biofilters or foam fractionators, offer cost-effective quality maintenance where advanced systems are impractical. Constructed wetlands or plant-based polishing units further refine water treatment [4]. To counter evaporation, which alters salinity and nutrient levels, simple measures like tank shading with netting, floating covers (e.g., polystyrene sheets) or windbreaks reduce water loss economically [44]. Optimized water replacement involves manual monitoring of parameters like temperature, pH, dissolved oxygen, nitrate and TDS, allowing strategic small-volume exchanges to manage buildup without harming fish health [5]. Additionally, integrating rainwater harvesting or basic storage reservoirs helps offset evaporation, boosting system resilience [45-47].

These practices, when combined, can maintain high water recirculation rates while reducing operational costs and the ecological footprint of aquaculture in water-scarce or environmentally sensitive areas.

Nutrient Management: Balancing Inputs and Outputs for Internal Circularity

Effective nutrient management is essential for preserving water quality, reducing waste and enhancing resource circularity in Recirculating

Aquaculture Systems (RAS). Nutrient inputs from fish feed and water, alongside outputs like fish biomass, dissolved nitrogenous compounds, phosphates and solid organic waste, require careful balance to maintain system stability and efficiency. In small-scale, low-tech RAS common in Indonesia, practical approaches can optimize nutrient use while supporting fish health and sustainability [48, 49].

Key internal strategies include optimized feeding practices, where overfeeding is minimized through stage-specific protocols tailored to biomass, water temperature and feed conversion ratios (FCR), lowering excess nutrients and costs [50, 51]. In smallholder contexts, manually adjusting feed based on fish appetite proves effective. Biofilter management enhances nutrient processing by converting ammonia and nitrite into nitrate via healthy biofilms, maintained through regular cleaning and manual checks of color and thickness, especially without automated tools [5]. Developing a microbial loop with carbon sources like molasses or rice bran fosters beneficial bacteria, assimilating nitrogen into harvestable biomass via foam fractionation or probiotics [52]. Additionally, diverting nitrate-rich effluent to grow microalgae or microbial flocs reduces accumulation while yielding feed supplements or biofertilizers [18, 19, 28].

In tropical environments, high temperatures accelerate nutrient turnover and microbial growth, enhancing biomass production but requiring vigilant monitoring with simple water quality testing kits to prevent imbalances [30, 40, 53, 54]. These strategies enable smallholder RAS operators to maintain system stability, reduce costs and enhance resource circularity.

Energy Efficiency: Resource Recirculation with Minimal Energy Inputs

Energy consumption in Recirculating Aquaculture Systems (RAS) significantly impacts operational costs, driven by water circulation, aeration, filtration and temperature control. In Indonesia's small-scale rural aquaculture, where energy costs can burden budgets, low-tech, energy-efficient solutions are vital for sustainability. Tropical climates lessen heating needs but heighten aeration and biological activity demands, requiring specific strategies [55].

To boost energy efficiency and internal circularity, low-energy pumping systems with appropriately sized submersible or centrifugal pumps, optimized plumbing and gravity-fed designs reduce electricity use [4]. Manual aeration adjustments, based on periodic oxygen checks and fish behavior, enhance efficiency by intensifying during feeding peaks and easing at night or low biomass phases [44]. In cooler tropical highlands, passive solar heating with greenhouse coverings or black-bottom tanks maintains water temperatures without extra energy [56, 57]. Optimized designs, like deep raceways, circular tanks with central drains and radial flow settlers, improve circulation, cutting high-powered aeration needs [5]. Additionally, integrating sunlight for microalgae cultivation supports nutrient recycling and biomass production, further lowering energy demands [58, 59].

These strategies enable smallholder RAS operators in tropical regions to lower costs, maintain system performance and enhance environmental sustainability.

Non-Aquaponics Applications for Treated RAS Outputs

While aquaponics is widely known for integrating aquaculture with hydroponic plant systems, its technical complexity, high capital investment and market limitations restrict its viability for smallholder and tropical aquaculture systems like those in Indonesia [39]. To expand circular economy opportunities, non-aquaponics applications offer accessible, low-cost alternatives for repurposing treated water, dissolved nutrients and solid by-products, improving economic viability and sustainability for small-scale Recirculating Aquaculture Systems (RAS).

In Indonesia, where smallholder RAS operations typically lack advanced infrastructure, repurposing treated outputs into high-value products is essential. Low-tech methods well-suited for tropical climates include microalgae cultivation, microbial biomass production and solid waste valorization. These applications leverage warm temperatures and abundant sunlight to accelerate biological processes, enhancing resource recovery while reducing costs and environmental impacts [19, 28, 32].

Microalgae Production Using Nutrient-Rich Treated RAS Water

Post-biofiltration effluent in RAS systems is rich in nitrates, phosphates and dissolved organic carbon, making it an ideal medium for microalgae cultivation. This process removes excess nutrients while generating biomass for aquafeed, biofertilizers, biofuels or even cosmetic applications [18, 19]. In Indonesia's tropical climate, high temperatures (25–32°C) and abundant sunlight accelerate algal growth, boosting production efficiency without the need for artificial heating or lighting [30, 40].

Small-scale rural producers can adopt simple systems such as open ponds, raceway tanks or plastic bag bioreactors with minimal infrastructure and technical demands. Harvesting techniques like sedimentation, filtration, solar drying or natural flocculation using moringa seed extract enable efficient biomass collection without mechanized tools [28, 29]. Key microalgae species such as *Chlorella vulgaris*, *Scenedesmus obliquus* and *Nannochloropsis* sp. produce protein-rich biomass containing PUFAs, essential amino acids and pigments like astaxanthin, valuable as feed additives for fish and shrimp [28, 60].

Beyond aquafeed, microalgae-derived biofertilizers improve soil microbial health and nutrient availability, supporting organic crop production [61]. While smallholders may face challenges scaling biofuel production, lipid-rich algae still offer potential for biogas generation in community-based systems.

Microbial Biomass Production for Probiotics and Biofertilizers

Treated RAS water also supports the cultivation of heterotrophic and nitrifying bacteria, offering applications as probiotics for aquaculture or biofertilizers for agriculture. These microbial cultures stabilize water chemistry, enhance fish gut health and outcompete pathogens in RAS tanks while enriching soil fertility when applied to crops [18, 19].

Low-tech fermentation systems such as barrel-based digesters and compost tea fermenters allow smallholders to produce microbial biomass using treated water and affordable carbon sources like molasses or rice bran. Key species like *Bacillus subtilis*, *Lactobacillus plantarum* and *Pseudomonas putida* improve water quality and reduce disease risks in aquaculture operations [62, 63].

In tropical Indonesia, elevated temperatures accelerate microbial metabolism, reducing culture times and boosting biomass yields [64, 65]. Locally adapted microbial consortia are often better suited to regional water chemistry and climatic conditions than imported commercial products. Community-managed fermentation facilities further reduce individual production costs while fostering knowledge exchange and cooperation among smallholder farmers [66].

Solid By-Products Repurposing

Solid waste generated from Recirculating Aquaculture Systems (RAS) including fish feces, uneaten feed and biofilm debris is often undervalued despite its significant potential for reuse [49]. After undergoing dewatering or partial treatment, these organic residues can be transformed into valuable materials such as soil conditioners, compost substrates or supplemental feed ingredients. Stabilization methods like drying, composting or fermentation can convert these by-products into nutrient-rich resources suitable for agricultural or aquaculture applications [67–69].

In Indonesia, where integrated farming practices are widespread, reusing aquaculture solids in adjacent crop fields or agroforestry systems presents a practical circular economy strategy. Research indicates that biofertilizers made from treated RAS sludge can increase soil organic content and reduce reliance on synthetic fertilizers, offering both environmental and financial advantages [30, 35]. Composting transforms nitrogen- and phosphorus-rich solids into organic soil conditioners, enhancing soil health while closing nutrient loops. Fish waste solids, after drying and fermenting, can also be incorporated into cost-effective feed formulations for omnivorous and detritivorous fish species [25].

Anaerobic digestion of these solids produces biogas (mostly methane) and nutrient-rich digestate, usable as liquid fertilizer or soil conditioner [37]. Simple, community-scale facilities featuring covered composting pits, shared drying racks, fermentation tanks and biogas digesters enable smallholder groups to manage by-product valorization collaboratively, improving cost efficiency and operational feasibility.

The non-aquaponics applications of treated RAS resources offer significant opportunities for enhancing circularity and economic resilience in tropical aquaculture systems. By integrating microalgae cultivation, microbial biomass production and by-product valorization into RAS operations, smallholder farmers can generate additional income, reduce input costs and strengthen environmental stewardship. The feasibility of these innovations in tropical Southeast Asia is enhanced by favorable climate conditions, year-round production cycles and growing regional demand for sustainable agricultural inputs. Table 12 summarizes the potential non-aquaponics applications of treated RAS resources and their specific advantages for tropical aquaculture systems.

Table 12: Non-aquaponics circular applications of treated RAS outputs in tropical systems

Resource Type	Application	Product	Tropical Advantage
Treated Water	Microalgae production	Feed, fertilizer, biofuels	High sunlight, warm temperatures
Dissolved Nutrients	Microbial biomass	Probiotics, biofertilizers	Fast microbial growth cycles
Solid By-products	Compost, biogas, feed	Organic fertilizer, methane	Rapid composting, efficient digestion

Tropical Climate Considerations for Resource Recovery

Indonesia's tropical climate presents both opportunities and operational challenges for resource recovery in Recirculating Aquaculture Systems (RAS). Warm temperatures and high humidity accelerate biological processes, enhancing the efficiency of organic waste decomposition, composting, microbial biomass production and microalgae cultivation [18, 30, 40]. These climatic conditions naturally support faster generation of fish feed additives, biofertilizers, biogas and other valorized by-products, reducing the time and energy typically required in temperate systems.

However, the same environmental conditions also increase risks such as nutrient buildup, oxygen depletion and pathogen proliferation, particularly in open, low-tech systems common among smallholder farmers [5, 70]. Rapid nutrient turnover can lead to ammonia spikes, nitrate accumulation and eutrophication if not carefully managed [71, 72]. Additionally, high humidity can promote odor issues and nutrient leaching during solid waste handling [16].

Effective management in these conditions relies on practical, low-cost and labor-based strategies suited to smallholder aquaculture operations. Simple adaptations such as covered composting pits, plastic-lined anaerobic digesters, manual water quality monitoring and natural shading systems help maintain system stability while leveraging tropical advantages [1, 30, 44]. Open-pond and raceway systems constructed from readily available materials like plastic sheeting and cement tanks allow for efficient microalgae production without costly automation [28].

The tropical climate also enhances resource conversion rates and reduces external energy demands. High solar irradiance supports passive heating and natural light-based cultivation of microalgae and beneficial microbes, minimizing energy inputs compared to temperate systems [37, 73]. Accelerated composting and anaerobic digestion processes further optimize resource recovery cycles in tropical conditions [30, 40].

To prevent operational risks, manual oversight, regular harvesting schedules and system flow management are essential. These practices are compatible with the labor-rich, low-capital nature of smallholder aquaculture operations, offering scalable, sustainable solutions without the need for sophisticated technology [74, 75].

In sum, while Indonesia's tropical climate accelerates biological resource recovery processes and reduces operational costs, it simultaneously demands careful management to mitigate risks associated with rapid nutrient cycling and pathogen outbreaks. Incremental, context-appropriate improvements in water reuse, nutrient recovery and by-product valorization are both feasible and advantageous for small-scale RAS operators. These locally adapted, circular strategies form a resilient foundation for advancing sustainable aquaculture systems in tropical Southeast Asia.

Economic and Social Benefits of Circular Resource Utilization

The integration of circular economy (CE) practices within Recirculating Aquaculture Systems (RAS) presents a range of economic and social advantages, particularly for emerging aquaculture regions such as Indonesia. By shifting away from the traditional linear model of "take-make-dispose" toward regenerative, closed-loop systems, RAS operators can achieve measurable cost savings, unlock new revenue opportunities and promote local employment. These outcomes carry particular significance in rural and smallholder contexts, where enhancing economic resilience and fostering community-based development remain key priorities.

While much of the discourse around circular aquaculture has focussed on environmental benefits like nutrient load reduction and water savings [4], increasing attention is now directed toward the socio-economic returns of circular resource strategies. These gains are particularly significant for smallholder farmers and aquaculture-dependent communities in tropical Southeast Asia, where livelihoods closely rely on sustainable aquaculture productivity.

By integrating treated water reuse, nutrient recovery and by-product valorization, circular aquaculture models deliver both direct operational savings and wider socio-economic benefits, supporting the United Nations Sustainable Development Goals (SDGs), notably SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 8 (Decent Work and Economic Growth) and SDG 12 (Responsible Consumption and Production) [17].

Economic Advantages through Cost Savings and New Revenue Streams

Circular resource management in RAS effectively reduces operational costs by minimizing dependency on water, feed and energy. Water reuse rates of 90–99% significantly cut expenses associated with extraction and wastewater discharge [38, 76]. Nutrient recovery initiatives converting biofiltration by-products into microalgae-based feeds, microbial biomass or organic fertilizers further lower reliance on external inputs [18, 19].

Producing microalgae with nutrient-rich effluent offers a practical feed supplement strategy, partially replacing costly fishmeal and reducing feed expenses, a major operational burden in Indonesian aquaculture [18, 19]. Similarly, repurposing solid fish waste into organic composts and soil enhancers lowers fertilizer and waste disposal costs [38, 76].

Beyond operational savings, circular models unlock new income opportunities. Value-added products such as microalgal biomass, probiotics and organic fertilizers derived from RAS by-products have commercial applications in aquaculture, agriculture and cosmetics [18, 19]. In Indonesia, microalgae products like spirulina can command US$30–50 per kilogram in niche health markets [2], while probiotics and organic fertilizers meet growing demand in organic farming [77].

Broader Social Benefits: Employment, Empowerment and Food Security

Circular economy initiatives in RAS generate substantial social value through job creation and community empowerment. Activities such as microalgae cultivation, composting, fermentation and by-product packaging introduce labor-intensive, low-tech employment opportunities in rural areas with limited job prospects [7, 78]. These positions are often accessible to women and younger workers, supporting gender-inclusive and youth employment [79].

Community-based cooperative models have proven effective for managing decentralized resource recovery and by-product processing in rural aquaculture regions. Shared facilities like microalgae raceways, fermentation units and composting pits enable smallholders to pool capital and labor, reinforcing local economic participation and social cohesion [7, 80, 81]. These collaborative frameworks also strengthen farmers' collective bargaining power and facilitate knowledge exchange [82, 83].

Circular RAS practices contribute indirectly to food and nutritional security by lowering production costs, diversifying household incomes and improving local access to nutrient-rich fish and chemical-free produce. By supporting organic crop cultivation in peri-urban and rural areas, organic fertilizers and biofertilizers produced from RAS outputs enhance food availability and health outcomes [2, 84].

Moreover, participatory, community-managed aquaculture initiatives align well with Indonesian rural traditions, making circular approaches culturally compatible and socially acceptable while advancing sustainable aquaculture without capital-intensive technologies [7, 81].

Environmental and Climate Resilience Co-Benefits

In addition to economic and social impacts, circular RAS systems mitigate environmental risks by reducing nutrient discharge and water consumption. Recycling nutrients within aquaculture operations or redirecting them for agricultural use curbs water pollution and safeguards freshwater resources for communal needs [31, 85]. This approach also strengthens climate resilience by decreasing reliance on external inputs and diversifying income, helping smallholder operations adapt to droughts, water shortages or fluctuating input prices [79].

Moreover, integrating circular aquaculture models into local economies supports sustainable rural development in Southeast Asia. These initiatives promote inclusive growth, reduce poverty and enhance environmental sustainability, aligning with long-term regional development goals and policy priorities [1].

Implementation Challenges and Solutions for Circular Resource Utilization

While circular economy (CE) practices in Recirculating Aquaculture Systems (RAS) deliver notable environmental, economic and social benefits, their implementation in tropical, smallholder and resource-limited contexts faces significant technical, financial, environmental and institutional challenges. Constraints often involve the complexity of resource recovery technologies, infrastructure costs, knowledge gaps in non-traditional aquaculture applications and region-specific environmental factors. Overcoming these barriers requires affordable, scalable and locally adapted solutions to unlock the potential of circular aquaculture in Indonesia and similar regions.

Technical Constraints and Adaptive Solutions

One of the primary technical obstacles lies in producing microalgae and microbial biomass at small scales without access to controlled environments and advanced equipment. Maintaining stable nutrient, light and temperature conditions in tropical regions—where environmental parameters fluctuate rapidly—remains difficult [18, 19]. Achieving consistent, commercially viable microalgae or microbial biomass production within RAS requires precise control over parameters such as nutrient concentrations, light intensity, aeration and contamination risks [28, 29], which can be beyond the reach of smallholders.

To address this, low-cost, modular systems such as plastic-lined open ponds, cement tanks and barrel fermenters have been recommended [28, 52]. Microbial biomass can be cultivated in simple fermentation units using treated RAS water and inexpensive carbon sources like molasses or rice bran. Operational efficiency improves with standardized, context-specific procedures for managing water quality, harvesting, nutrient adjustment and contamination risks [86]. Additionally, community cooperatives can pool resources to establish shared microalgae and microbial production facilities, reducing individual financial burdens.

Economic Barriers and Financial Mechanisms

High capital costs for by-product processing infrastructure—such as composting pits, biogas digesters and microalgae raceways—pose a persistent challenge for smallholders, despite long-term benefits [48, 87]. Financing options such as microloans, government grants, tax incentives and cooperative investment schemes are crucial for lowering entry barriers [7, 80, 81, 88].

Proposed solutions include community-shared facilities that enable producers to collectively process resources while distributing investment and operational costs [84]. Microfinance initiatives and targeted subsidies can further support individual farmers adopting circular aquaculture technologies [2, 35].

Knowledge and Capacity Limitations

A significant barrier to circular aquaculture adoption lies in the limited technical expertise and management experience among farmers, particularly in areas beyond aquaponics, such as microbial biomass cultivation, composting and biofertilizer production [19, 89, 90].

Addressing this requires expanding extension services and farmer education programs tailored to low-tech, tropical systems. Community-based training, on-farm demonstrations and peer-to-peer knowledge exchange platforms have proven effective [7, 80, 81]. Incorporating circular economy topics into vocational aquaculture curricula would also help develop long-term capacity. National extension services should provide hands-on training in microalgae cultivation, probiotic culture and organic waste management [1]. Farmer Field Schools (FFS) can promote practical learning and collaborative problem-solving through peer-to-peer demonstrations [35]. Additionally, locally tailored open-source technical manuals, made available in digital formats, can improve access to essential knowledge on affordable circular aquaculture practices [91].

Environmental Risks in Tropical Conditions

High ambient temperatures in tropical aquaculture systems accelerate microbial processes, destabilize nutrient balances and increase pathogen risks. Open, unshaded systems are particularly vulnerable to rapid nutrient cycling, oxygen depletion and evaporative losses [30, 40]. Rapid nutrient turnover in tropical aquaculture systems increases the risk of nitrate accumulation, ammonia spikes and pathogen outbreaks [71, 72].

Simple design modifications and adaptive management practices can effectively address these risks. Adaptive management practices and the use of locally adapted microbial and algal strains improve system stability under high-temperature conditions [74, 75]. Regular water quality checks using simple test kits enable farmers to detect and respond to problems early [5]. Additionally, natural shading and evaporation control measures, such as floating covers, perimeter plantings or shade netting, help regulate temperatures and minimize water loss in open systems [44].

Institutional and Policy Constraints

In several Southeast Asian countries, regulatory frameworks for aquaculture effluent discharge, biofertilizer production and microalgae commercialization remain fragmented, poorly enforced or entirely lacking. This regulatory uncertainty deters investment in circular resource utilization among smallholder farmers [2]. The absence of clear standards, certification schemes and legal guidelines complicates market access for circular aquaculture products.

To address this, governments should promote public-private partnerships (PPPs) to pilot circular innovations, establish formal guidelines for by-product utilization and integrate CE principles into national aquaculture development strategies. Introducing eco-labels and sustainability certifications for zero-waste aquaculture products can enhance market value and incentivize broader adoption [28].

An integrated summary of the major constraints and practical, smallholder-appropriate solutions for circular resource utilization in tropical aquaculture is presented in Table 15.

Table 13: Integrated summary of challenges and contextual solutions for integration of circular economy in Recirculating Aquaculture Systems (RAS)

Dimension	Challenge	Recommended Smallholder Solution
Technical	Microalgae production complexity	Plastic bag bioreactors [28]
Economic	Infrastructure costs	Cooperative shared facilities [84]
Knowledge	Limited CE expertise	Farmer Field Schools [35]
Environmental	Pathogen risks	Manual monitoring kits [5]
Policy	Regulatory fragmentation	Biofertilizer certification [2]

Potential Negative Economic, Social and Environmental Impacts of Circular Economy in RAS

The implementation of Circular Economy in Recirculating Aquaculture Systems (CERAS) presents several significant challenges, as outlined in Table 16 One major issue is the displacement of traditional livelihoods, creating a noticeable social divide between high-tech adopters and conventional fishers. This shift not only disrupts established communities but also demands advanced technical skills, risking the obsolescence of general aquaculture labor. Additionally, the high capital investment required for CERAS infrastructure, such as biofilters, tanks and pumps, poses a barrier, particularly for small-scale farmers who may lack the financial and human resources to participate effectively.

Furthermore, the economic viability of CERAS is hampered by elevated operational costs and potential market saturation. The reliance on imported fish feed, seed and technical components adds another layer of complexity, increasing expenses. Community resistance may also arise due to unfamiliar practices, complicating adoption. Environmentally, the high energy demand and waste management issues, including the risk of invasive species, underscore the need for careful planning to mitigate negative impacts while striving for sustainability in aquaculture practices.

Table 14: Potential negative economic, social and environmental impacts of implementation of circular economy in Recirculating Aquaculture Systems (RAS).

Dimension	Potential Negative Impacts	Details
Social	Displacement of traditional livelihoods	RAS with relatively high technology compared to traditional open systems might sideline traditional fishers and pond farmers, creating social or even welfare gap
	Skills and labor mismatch	RAS requires more technical knowledge which consequently might make general aquaculture labor obsolete.
	Inequitable access	Rural or small-scale farmers might not have enough capital, both financial and human, to start CE-RAS.
	Community resistance	There is a probability of community resistance or even rejection when there are unfamiliar practices trying to alter local, deeply-rooted practices. Communities might not agree to take the risk.
Economic	High capital and operational costs	RAS infrastructure (biofilters, tanks, pumps) and energy use are costly even when we present low-cost small-scale alternatives. Many might not have necessary fund.
	Market saturation and overproduction	If low-cost CE-RAS succeeds, it might contribute to oversupply and eventually, falling prices, especially when there is no or limited, market planning.
	Continued reliance on external inputs	Fish feed, seed and technical components are often imported and expensive.
	Technological lock-in	Once people are committed to specific CE-RAS technology, it might be hard for them to switch to other types of technology because it will require more fund and know-how.
Environmental	High energy demand	RAS operations are electricity intensive. Unless we unplug and rely on renewable energy (e.g., solar panels), the environmental benefits from running CE-RAS might be negated by its emission because of reliance to fossil fuels.
	Concentrated	Wastewater, sludge and bio-solids can

	waste handling risks	cause pollution if not properly managed.
	Risk of non-native species escape	If containment fails, farmed species can become invasive and harm local ecosystems.
	Resource competition	Competes for clean water, land (e.g. for integrated hydroponics) and alternative feed resources (e.g. insects, algae).

Prospects for Circular Resource Utilization in RAS

The integration of circular economy principles into Recirculating Aquaculture Systems (RAS) in Indonesia offers significant opportunities for enhancing both environmental sustainability and economic resilience in the coming years. As global aquaculture demand rises and environmental pressures intensify, developing accessible, scalable and climate-adapted circular models will be essential for ensuring the long-term viability of smallholder aquaculture operations in tropical regions.

Scaling Up Microalgae and Microbial Biomass Production

One of the most promising future directions lies in the expansion of microalgae and microbial biomass cultivation using RAS effluent nutrients. As studies have shown, microalgae systems can fully uptake nitrates and phosphates, producing biomass suitable for use in aquaculture feed, organic fertilizers and bioproducts [18]. In Indonesia's warm climate, rapid growth rates of microalgae and heterotrophic bacteria offer a strategic advantage for resource recovery without the need for energy-intensive systems.

The prospects include the development of regional pilot projects and community-based cooperative models that pool resources, land and labor to operate low-tech algae ponds or microbial fermenters. Such models would not only improve resource efficiency but also provide employment and income diversification opportunities for rural communities [7, 80, 81].

Developing Affordable, Tropical-Adapted Processing Technologies

Another priority is the innovation of low-cost, tropical-adapted by-product processing technologies. Techniques such as manual drying racks for solid waste, passive solar dryers for microalgae and simple fermentation barrels for microbial cultures require minimal capital investment and can be easily integrated into smallholder operations. Research partnerships between universities, government extension services and farmer cooperatives can help refine these technologies for widespread adoption in Indonesia's aquaculture sector [91, 92].

Encouraging localized technology innovation, drawing on indigenous knowledge and available materials, will be essential in ensuring scalability and economic feasibility, particularly in regions with limited infrastructure.

Public-Private and Farmer Cooperative Partnerships

To finance and operationalize these circular initiatives at scale, collaborative partnerships between public institutions, private investors and farmer cooperatives will be critical. Public-private partnerships (PPPs) can support the establishment of shared by-product processing facilities, algae cultivation centers and training hubs, while government agencies provide regulatory support and fiscal incentives [93, 94].

Additionally, promoting decentralized, cooperative business models, where groups of smallholder farmers collectively manage waste processing and biomass production units, has proven effective in increasing resource access and reducing individual investment burdens. These models foster inclusive growth and distribute economic benefits equitably across rural communities [7, 80].

Positioning RAS as a Regional Model for Resource-Efficient Aquaculture

With the successful development and scaling of these low-tech, circular resource management strategies, Indonesia has the potential to position its RAS sector as a regional benchmark for resource-efficient aquaculture in Southeast Asia. As neighbouring countries face similar environmental and resource limitations, Indonesia's experience in applying circular economy principles in decentralized, smallholder contexts could inform broader regional sustainability frameworks [14, 48, 95].

International knowledge exchange platforms, technical collaboration initiatives and joint regional research projects could further accelerate innovation in tropical aquaculture sustainability, reinforcing the role of circular RAS as a model for balancing productivity, profitability and environmental stewardship [39, 96].

Conclusion

Integrating circular economy principles into Recirculating Aquaculture Systems (RAS) offers a transformative pathway for sustainable aquaculture in tropical smallholder settings like Indonesia. By repurposing treated water, nutrients and solid waste into valuable products such as microalgae, microbial biomass, organic fertilizers and biogas, circular RAS enhances resource efficiency, reduces operational costs and diversifies income for rural communities. Low-tech, climate-adapted strategies, such as gravity-based recirculation, composting and open-pond bioreactors, make these practices accessible to small-scale farmers, despite challenges like technical complexity, capital constraints and knowledge gaps. These solutions not only mitigate environmental impacts but also create jobs, strengthen food security and align with global sustainability goals. By scaling up cooperative models, fostering public-private partnerships and developing affordable technologies, Indonesia can position circular RAS as a regional model for resource-efficient aquaculture, driving economic resilience and environmental stewardship in Southeast Asia.

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References

1. FAO. The State of World Fisheries and Aquaculture 2022: Towards Blue Transformation [Internet]. FAO; 2022. Available from: http://www.fao.org/documents/card/en/c/cc0461en
2. FAO. The State of World Fisheries and Aquaculture 2020 [Internet]. Rome, Italy: FAO; 2020. Available from: http://www.fao.org/documents/card/en/c/ca9229en
3. Salam AD, Renaud N, Yannick L, Pascal F, Changey F. Effects of biofilter management modalities on the microbiological status in RAS water to avoid recording capacities of biofilms. Aquac Eng 2025; 110:102522.
4. Badiola M, Mendiola D, Bostock J. Recirculating Aquaculture Systems (RAS) analysis: Main issues on management and future challenges. Aquac Eng 2012; 51:26–35. https://linkinghub.elsevier.com/retrieve/pii/S014486091200060X
5. Martins CIM, Eding EH, Verdegem MCJ, Heinsbroek LTN, Schneider O, Blancheton JP *et al.* New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. Aquac

Eng 2010;43(3):83–93. http://dx.doi.org/10.1016/j.aquaeng.2010.09.002

6. Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ. The Circular Economy – A new sustainability paradigm? J Clean Prod 2017; 143:757–68. https://linkinghub.elsevier.com/retrieve/pii/S0959652616321023
7. Kirchherr J, Reike D, Hekkert M. Conceptualizing the circular economy: An analysis of 114 definitions. Resour Conserv Recycl 2017; 127:221–32. https://linkinghub.elsevier.com/retrieve/pii/S0921344917302835
8. Velenturf APM, Jensen PD, Purnell P, Jopson J, Ebner N. A call to integrate economic, social and environmental motives into guidance for business support for the transition to a circular economy. Adm Sci 2019; 9(4):92. https://www.mdpi.com/2076-3387/9/4/92
9. D'Amato D, Droste N, Allen B, Kettunen M, Lähtinen K, Korhonen J *et al*. Green, circular, bio economy: A comparative analysis of sustainability avenues. J Clean Prod 2017; 168:716–34. https://linkinghub.elsevier.com/retrieve/pii/S0959652617320425
10. Urbinati A, Chiaroni D, Chiesa V. Towards a new taxonomy of circular economy business models. J Clean Prod 2017; 168:487–98.
11. Kümmerer K, Clark JH, Zuin VG. Rethinking chemistry for a circular economy. Science (1979) 2020; 367(6476):369–70.
12. Naylor RL, Kishore A, Sumaila UR, Issifu I, Hunter BP, Belton B *et al*. Blue food demand across geographic and temporal scales. Nat Commun 2021;12(1):5413. //www.nature.com/articles/s41467-021-25516-4
13. Sreedevi CS, Salahudeen MR. Sustainability route for industry 4. 0: the future of global circular economic transition [Internet]. In: Zhang T, editor. Circular Economy - Recent Advances, New Perspectives and Applications. IntechOpen; 2021. Available from: https://www.intechopen.com/books/circular-economy-recent-advances-new-perspectives-and-applications/sustainability-route-for-industry-4-0-the-future-of-global-circular-economic-transition
14. Chary K, van Riel AJ, Muscat A, Wilfart A, Harchaoui S, Verdegem M *et al*. Transforming sustainable aquaculture by applying circularity principles. Rev Aquac 2024;16(2):656–73.
15. Fischer AD. Circular economy - forging institutions [Internet]. 2022; Available from: https://edepot.wur.nl/567287

16. Jacinda AK. Resirculating Aquaculture System (RAS) Technology Applications in Indonesia: A Review. Jurnal Perikanan dan Kelautan 2021;11(1):43.

17. UN. Transforming our world: the 2030 Agenda for Sustainable Development [Internet]. United Nations; 2015. Available from: https://docs.un.org/en/A/RES/70/1

18. Böpple H, Kymmell NLE, Slegers PM, Breuhaus P, Kleinegris DMM. Water treatment of recirculating aquaculture system (RAS) effluent water through microalgal biofilms. Algal Res 2024; 84:103798. https://linkinghub.elsevier.com/retrieve/pii/S2211926424004107

19. Dubo FAC. Circular economy in aquaculture: strategies to minimize waste and maximize efficiency. [Internet]. LinkedIn: From sea to table: the fascina Newsletter2024; Available from: https://www.linkedin.com/pulse/circular-economy-aquaculture-strategies-minimize-waste-cerda-dub%C3%B3-zmhre

20. Xu W, Xu Y, Su H, Hu X, Yang K, Wen G *et al*. Characteristics of Ammonia Removal and Nitrifying Microbial Communities in a Hybrid Biofloc-RAS for Intensive Litopenaeus vannamei Culture: A Pilot-Scale Study. Water (Basel) 2020; 12(11):3000.

21. Park NB, Park MS, Lee JH, Myeong JI. A Study of Nitrification Kinetics in the Biofilter Process for Aquaculture Water Treatment: A Review. Korean Journal of Fisheries and Aquatic Sciences 2013; 46(6):675–81.

22. Esteves AF, Soares SM, Salgado EM, Boaventura RAR, Pires JCM. Microalgal growth in aquaculture effluent: coupling biomass valorisation with nutrients removal. Applied Sciences 2022; 12(24):12608. Available from: https://www.mdpi.com/2076-3417/12/24/12608

23. Yaakob MA, Mohamed RMSR, Al-Gheethi A, Aswathnarayana Gokare R, Ambati RR. Influence of Nitrogen and Phosphorus on Microalgal Growth, Biomass, Lipid and Fatty Acid Production: An Overview. Cells 2021; 10(2):393.

24. Al-Othman AA, Selim MM. Integrated management of treated wastewater reuse in irrigation and its role in environment conservation. WIT Transactions on Ecology and the Environment [Internet] 2011; 153:447–54. Available from: http://library.witpress.com/viewpaper.asp?pcode=WS11-039-1

25. Azim ME, Little DC. Intensifying aquaculture production through new approaches to manipulating natural food. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 2007;1(62):1–23. http://www.cabidigitallibrary.org/doi/10.1079/PAVSNNR20061062

26. AlMomani F, Örmeci B. Assessment of algae-based wastewater treatment in hot climate region: Treatment performance and kinetics. Process Safety and Environmental Protection 2020; 141:140–9.

27. Dubó FAC. Circular economy in aquaculture: strategies to minimize waste and maximize efficiency. [Internet]. LinkedIn2024; Available from: https://www.linkedin.com/pulse/circular-economy-aquaculture-strategies-minimize-waste-cerda-dub%C3%B3-zmhre

28. Beal CM, Gerber LN, Sills DL, Huntley ME, Machesky SC, Walsh MJ *et al*. Algal biofuel production for fuels and feed in a 100-ha facility: A comprehensive techno-economic analysis and life cycle assessment. Algal Res 2015; 10:266–79.

29. Borowitzka MA. High-value products from microalgae—their development and commercialisation. J Appl Phycol 2013; 25(3):743–56. http://link.springer.com/10.1007/s10811-013-9983-9

30. Kurniawan SB, Ahmad A, Imron MF, Abdullah SRS, Othman AR, Hasan HA. Achieving a biocircular economy in the aquaculture sector through waste valorization. Toxics 2025; 13(2):131. https://www.mdpi.com/2305-6304/13/2/131

31. Chiquito-Contreras RG, Hernandez-Adame L, Alvarado-Castillo G, Martínez-Hernández MDJ, Sánchez-Viveros G, Chiquito-Contreras CJ *et al*. Aquaculture—production system and waste management for agriculture fertilization—a review. Sustainability 2022; 14(12):7257. Available from: https://www.mdpi.com/2071-1050/14/12/7257

32. Elgarahy AM, Eloffy MG, Priya AK, Yogeshwaran V, Yang Z, Elwakeel KZ *et al*. Biosolids management and utilizations: A review. J Clean Prod 2024; 451:141974. https://linkinghub.elsevier.com/retrieve/pii/S0959652624014227

33. Sharma B, Sarkar A, Singh P, Singh RP. Agricultural utilization of biosolids: A review on potential effects on soil and plant grown. Waste Management 2017; 64:117–32.

https://linkinghub.elsevier.com/retrieve/pii/S0956053X17301125

34. Kriesel W, McIntosh CS, Miller WP. The potential for beneficial re-use of sewage sludge and coal combustion by-products. J Environ Manage 1994; 42(4):299–315. https://linkinghub.elsevier.com/retrieve/pii/S0301479784710747
35. Kurniawan SB. A review of the future of biomass-based fertilizer in Indonesia. EPRA International Journal of Economic and Business Review 2023; 11(7):27–31. https://eprajournals.com/IJES/article/10949
36. Asiri F. Polyhydroxyalkanoates for Sustainable Aquaculture: A Review of Recent Advancements, Challenges and Future Directions. J Agric Food Chem 2024; 72(4):2034–58. https://pubs.acs.org/doi/10.1021/acs.jafc.3c06488
37. Ge X, Matsumoto T, Keith L, Li Y. Biogas energy production from tropical biomass wastes by anaerobic digestion. Bioresour Technol 2014; 169:38–44. https://linkinghub.elsevier.com/retrieve/pii/S0960852414009213
38. Zhang R, Chen T, Wang Y, Short M. Systems approaches for sustainable fisheries: A comprehensive review and future perspectives. Sustain Prod Consum 2023; 41:242–52. https://linkinghub.elsevier.com/retrieve/pii/S2352550923001999
39. Lal J, Vaishnav A, Deb S, Kashyap S, Debbarma P, Devati *et al*. Recirculatory aquaculture systems: a pathway to sustainable fish farming. Archives of Current Research International 2024; 24(5):799–810. https://www.journalacri.com/index.php/ACRI/article/view/756
40. Shitu A, Liu G, Muhammad AI, Zhang Y, Tadda MA, Qi W *et al*. Recent advances in application of moving bed bioreactors for wastewater treatment from recirculating aquaculture systems: A review. Aquac Fish 2022; 7(3):244–58.
41. Kuhn D. Ways to sustainably manage wastewater in ras - rastech magazinerastech magazine. Rastech [Internet] 2021; Available from: https://www.rastechmagazine.com/ways-to-sustainably-manage-wastewater-in-ras/
42. Teitge F, Peppler C, Steinhagen D, Jung-Schroers V. Water disinfection by ozonation has advantages over UV irradiation in a brackish water recirculation aquaculture system for Pacific white shrimp (*litopenaeus*

vannamei). J Fish Dis 2020; 43(10):1259–85. Available from: https://onlinelibrary.wiley.com/doi/10.1111/jfd.13238

43. Burgos-Morán R, Shaw J, Sánchez-Campuzano J. Simply low-cost recirculation aquaculture system for Amazonian native fish hatchery under controlled conditions. In: Proceedings of MOL2NET 2019, International Conference on Multidisciplinary Sciences, 5th edition. Sciforum.net: MDPI; 2019. page 6623. Available from: http://sciforum.net/conference/mol2net-05/paper/6623
44. Boyd CE, Tucker CS. Pond aquaculture water quality management [Internet]. E-Book. New York: Springer New York; 2012. Available from: https://link.springer.com/book/10.1007/978-1-4615-5407-3
45. Martínez-Espinosa RM. Controversy over the use of “shade covers” to avoid water evaporation in water reservoirs. Sustainability 2021;13(20):11234. https://www.mdpi.com/2071-1050/13/20/11234
46. Min TH, Gunasekaran K, Pudyastuti PS. Development of a sustainable technology in reducing reservoir evaporation. E3S Web of Conferences 2024; 517:4007. https://www.e3s-conferences.org/10.1051/e3sconf/202451704007
47. Simon K, Shanbhag R, Slocum AH. Reducing evaporative water losses from irrigation ponds through the reuse of polyethylene terephthalate bottles. Journal of Irrigation and Drainage Engineering 2016; 142(2):6015005. https://ascelibrary.org/doi/10.1061/%28ASCE%29IR.1943-4774.0000972
48. Campanati C, Willer D, Schubert J, Aldridge DC. Sustainable Intensification of Aquaculture through Nutrient Recycling and Circular Economies: More Fish, Less Waste, Blue Growth. Reviews in Fisheries Science & Aquaculture 2022; 30(2):143–69.
49. Mongirdas V, Žibienė G, Žibas A. Waste and its characterization in closed recirculating aquaculture systems – a review. Journal of Water Security 2017; 3(1). https://hdl.handle.net/20.500.12259/104282
50. Manam VK. Fish feed nutrition and its management in aquaculture. Int J Fish Aquat Stud 2023;11(2):58–61. https://www.fisheriesjournal.com/archives/?year=2023&vol=11&issue=2&part=A&ArticleId=2791

51. Zuriati Z, Supriyatna AR, Arifin O. Design and Development of Feeding Automation System and Water Quality Monitoring on Freshwater Fish Cultivation. IOP Conf Ser Earth Environ Sci 2022; 1012(1):012077. https://iopscience.iop.org/article/10.1088/1755-1315/1012/1/012077
52. Suneetha K, Kavitha K, Darwin CH. Biofloc Technology: An emerging tool for sustainable aquaculture. International Journal of Zoology Studies 2018; 3(1):87–98. http://rgdoi.net/10.13140/RG.2.2.18973.15840
53. Pratiwy FM. The overview of utilization of nutrient removal in recirculating aquaculture system. Global Scientific Journal 2020; 8(5):1617– 1620. https://www.globalscientificjournal.com/researchpaper/the_overview_of_utilization_of_nutrient_removal_in_recirculating_aquaculture_system.pdf
54. Crispim MC, Vieira ACB, Coelho SFM, Medeiros AMA. Nutrient uptake efficiency by macrophyte and biofilm: practical strategies for small-scale fish farming. Acta Limnologica Brasiliensia 2009; 21(4):387–91. https://actalb.org/article/627da1a4782aad07b35c1a5b/pdf/alb-21-4-387.pdf
55. Singh S, Marsh LS. Modelling thermal environment of a recirculating aquaculture facility. Aquaculture 1996; 139(1–2):11–8. https://linkinghub.elsevier.com/retrieve/pii/0044848695011641
56. Kusumah BR, Kostajaya A, Supriadi D, Nugraha EH, Siskandar R. Engineering of automatically controlled energy aeration systems for fisheries cultivation pools. Aquacultura Indonesiana 2020; 21(2):74. https://aquasiana.org/index.php/ai/article/view/207
57. Mahmoud AH. A Passive Solar-Thermal Aeration System for Rural Pond Aquaculture. [Internet]. 2016; Available from: https://tspace.library.utoronto.ca/bitstream/1807/75347/2/Mahmoud_Ahmed_201611_MAS_thesis.pdf
58. Turcios A, Papenbrock J. Sustainable treatment of aquaculture effluents—what can we learn from the past for the future? Sustainability 2014; 6(2):836–56. https://www.mdpi.com/2071-1050/6/2/836
59. Villanova V, Roques JAC, Forghani B, Shaikh KM, Undeland I, Spetea C. Two-phase microalgae cultivation for RAS water remediation and high-value biomass production. Front Plant Sci 2023; 14:1186537.

https://www.frontiersin.org/articles/10.3389/fpls.2023.1186537/full

60. Hemaiswarya S, Raja R, Ravi Kumar R, Ganesan V, Anbazhagan C. Microalgae: a sustainable feed source for aquaculture. World J Microbiol Biotechnol [Internet] 2011; 27(8):1737–46. http://link.springer.com/10.1007/s11274-010-0632-z

61. Alobwede E, Cotton A, Leake JR, Pandhal J. The fate and distribution of microalgal nitrogen when applied as an agricultural soil fertiliser and its effect on soil microbial communities. Phycology 2022; 2(3):297–318. https://www.mdpi.com/2673-9410/2/3/16

62. Blancheton JP, Attramadal KJK, Michaud L, d'Orbcastel ER, Vadstein O. Insight into bacterial population in aquaculture systems and its implication. Aquac Eng 2013; 53:30–9. https://linkinghub.elsevier.com/retrieve/pii/S0144860912000933

63. Rurangwa E, Verdegem MCJ. Microorganisms in recirculating aquaculture systems and their management. Rev Aquac 2015; 7(2):117–30. https://onlinelibrary.wiley.com/doi/10.1111/raq.12057

64. Cahyani F, Ardi A, Samudra TT, Budiman A, Suyono EA. Biomass productivity and lipid content between natural mixed culture consortia and artificial mixed culture. In: AIP Conference Proceedings. American Institute of Physics Inc.; 2020.

65. Nur F, Erfianti T andeska DP, Egistha Putri RA, Nurafifah I, Sadewo BR *et al*. Enhancement of microalgal metabolite production through euglena sp. Local strain and glagah strain consortia. Biosaintifika: Journal of Biology & Biology Education 2023; 15(1):36–47. https://journal.unnes.ac.id/nju/index.php/biosaintifika/article/view/41895

66. Valle-Vargas MF, Ruiz-Pardo RY, Villamil-Díaz L, Quintanilla-Carvajal MX. Production of a potential multistrain probiotic in co-culture conditions using agro-industrial by-products-based medium for fish nutrition. BMC Biotechnol 2023; 23(1):54. https://bmcbiotechnol.biomedcentral.com/articles/10.1186/s12896-023-00822-5

67. Delaide B, Monsees H, Gross A, Goddek S. Aerobic and Anaerobic Treatments for Aquaponic Sludge Reduction and Mineralisation. In: Goddek S, Joyce A, Kotzen B, Burnell G, editors. Aquaponics Food

Production Systems. Cham: Springer International Publishing; 2019. page 247–66.

68. Tetreault J, Fogle R, Guerdat T. Anaerobic Mineralization of Recirculating Aquaculture Drum Screen Effluent for Use as a Naturally Derived Nutrient Solution in Hydroponic Cropping Systems. Conservation 2021;1(3):151–67.

69. Lee J, Kim IS, Emmanuel A, Koh SC. Microbial valorization of solid wastes from a recirculating aquaculture system and the relevant microbial functions. Aquac Eng 2019; 87:102016. https://linkinghub.elsevier.com/retrieve/pii/S0144860919300524

70. Lindholm-Lehto P. Water quality monitoring in recirculating aquaculture systems. Aquaculture, Fish and Fisheries 2023; 3(2):113–31. https://onlinelibrary.wiley.com/doi/10.1002/aff2.102

71. Lo LSH, Xu Z, Lee SS, Lau WK, Qiu JW, Liu H *et al*. How elevated nitrogen load affects bacterial community structure and nitrogen cycling services in coastal water. Front Microbiol 2022; 13:1062029. https://www.frontiersin.org/articles/10.3389/fmicb.2022.1062029/full

72. Suwartha N, Pujiastuti DR. Enhancing removal efficiency of ammonia and nitrate in shrimp farm wastewater using biofloc technology and effective microorganisms 4(Em4). International Journal of Technology 2017; 8(6):1021. http://ijtech.eng.ui.ac.id/article/view/685

73. Feder F. Recycling organic waste products in a tropical context [Internet]. In: Valentin C, editor. Soils as a Key Component of the Critical Zone 5. Wiley; 2018. page 211–34. Available from: https://onlinelibrary.wiley.com/doi/10.1002/9781119438298.ch9

74. Chaiwongsai J. Automatic control and management system for tropical hydroponic cultivation [Internet]. In: 2019 IEEE International Symposium on Circuits and Systems (ISCAS). Sapporo, Japan: IEEE; 2019. page 1–4. Available from: https://ieeexplore.ieee.org/document/8702572/

75. Shamshiri RR, Mahadi MR, Thorp KR, Ismail WIW, Ahmad D, Man HC. Adaptive management framework for evaluating and adjusting microclimate parameters in tropical greenhouse crop production systems [Internet]. In: Jurić S, editor. Plant Engineering. InTech; 2017. Available from: http://www.intechopen.com/books/plant-engineering/adaptive-

management-framework-for-evaluating-and-adjusting-microclimate-parameters-in-tropical-green

76. Engle C, Kumar G, Van Senten J. Resource-use efficiency in US aquaculture: farm-level comparisons across fish species and production systems. Aquac Environ Interact 2021; 13:259–75. https://www.int-res.com/abstracts/aei/v13/p259-275/

77. Sarbani NMM, Yahaya N. Advanced development of bio-fertilizer formulations using microorganisms as inoculant for sustainable agriculture and environment – a review. Malaysian Journal of Science Health & Technology 2022; 8(1):92–101. https://mjosht.usim.edu.my/index.php/mjosht/article/view/228

78. Tashtamirov M. The circular economy and regional economic development. E3S Web of Conferences [Internet] 2023; 431:7003. Available from: https://www.e3s-conferences.org/10.1051/e3sconf/202343107003

79. Rajee O, Mun ATK. Impact of aquaculture on the livelihoods and food security of rural communities. Int J Fish Aquat Stud 2017; 5(2):278–83. https://www.fisheriesjournal.com/archives/2017/vol5issue2/PartD/5-1-81-919.pdf

80. Jensen HH. For manufacturers, the circular economy strengthens supply chains. Here’s how [Internet]. Manufacturing and Value Chains 2024; Available from: https://www.weforum.org/stories/2024/02/how-manufacturers-could-lead-the-way-in-building-the-circular-economy/

81. Ismaeel S. Closing the Loop: Harnessing Circular Economy Strategies for Climate Change Mitigation. Horizons 2024;114–22.

82. Lutz J, Smetschka B, Grima N. Farmer cooperation as a means for creating local food systems—potentials and challenges. Sustainability 2017; 9(6):925. https://www.mdpi.com/2071-1050/9/6/925

83. Ziegler R, Poirier C, Lacasse M, Murray E. Circular economy and cooperatives—an exploratory survey. Sustainability 2023; 15(3):2530. https://www.mdpi.com/2071-1050/15/3/2530

84. Colson G. Alternative approaches for sharing machinery, labor and other resources among small- and medium-sized agricultural producers [Internet]. 2008; Available from: https://lib.dr.iastate.edu/rtd/15326/

85. Verdegem MCJ. Nutrient discharge from aquaculture operations in

function of system design and production environment. Rev Aquac 2013; 5(3):158–71. https://onlinelibrary.wiley.com/doi/10.1111/raq.12011

86. Supajaruwong S, Satanwat P, Pungrasmi W, Powtongsook S. Design and function of a nitrogen and sediment removal system in a recirculating aquaculture system optimized for aquaponics. Environmental Engineering Research 2020; 26(2):190494. http://eeer.org/journal/view.php?doi=10.4491/eer.2019.494

87. Regueiro L, Newton R, Soula M, Méndez D, Kok B, Little DC *et al*. Opportunities and limitations for the introduction of circular economy principles in EU aquaculture based on the regulatory framework. J Ind Ecol 2022; 26(6):2033–44. https://onlinelibrary.wiley.com/doi/10.1111/jiec.13188

88. Budiman I, Takama T, Pratiwi L. Role of microfinance to support agricultural climate change adaptations in Indonesia: Encouraging private sector participation in climate finance. 2016.

89. Ende S, Henjes J, Spiller M, Elshobary M, Hanelt D, Abomohra A. Recent advances in recirculating aquaculture systems and role of microalgae to close system loop. Bioresour Technol 2024; 407:131107. https://linkinghub.elsevier.com/retrieve/pii/S0960852424008113

90. Cozzolino M, Salomone R, Mondello G, Gulotta TM. How intensive aquaculture is facing the challenge of the transition to a circular economy: evidence from a literature review. [Internet]. In: Half-way Through Agenda 2030: Assessing the 5Ps of SDGs (People, Planet, Prosperity, Peace and Partnership). Universiti Kebangsaan Malaysia (UKM), Malaysia: 2023. page 346–597.Available from: https://www.researchgate.net/publication/376191381_How_intensive_aquaculture_is_facing_the_challenge_of_the_transition_to_a_circular_economy_evidence_from_a_literature_review_ISBN_978-967-26554-1-1

91. Lakitan B. Inclusive and Sustainable Management of Suboptimal Lands for Productive Agriculture in Indonesia [Pengelolaan Lahan Suboptimal yang Inklusif dan Berkelanjutan untuk Mewujudkan Pertanian yang Produktif di Indonesia]. Jurnal Lahan Suboptimal 2014; 3(2):181–92. https://jlsuboptimal.unsri.ac.id/index.php/jlso/article/view/126

92. Stone S, Langford Z, Arsyi R, Lapong I, Zach Z, Ruhon R *et al*. Technology adoption by smallholder farmers: the case of drying technology in the Indonesian seaweed industry. J Agribus Dev Emerg

Econ 2025; 15(3):486–99. https://www.emerald.com/insight/content/doi/10.1108/JADEE-01-2023-0011/full/html

93. Akomea-Frimpong I, Jin X, Osei Kyei R, Tetteh PA, Tumpa RJ, Ofori JNA *et al*. A review of circular economy models and success factors on public-private partnership infrastructure development. Built Environment Project and Asset Management 2023; 14(1):109–26. https://doi.org/10.1108/BEPAM-01-2023-0014

94. Pavliashvili S, Papachashvili N, Mikaberidze T. Public-private partnership to scale up circular economy (The georgia case) [Internet]. In: Challenges in the Turbulent Economic Environment and Organizations' Sustainable Development. University of Maribor Press; 2024. page 355–68. Available from: https://press.um.si/index.php/ump/catalog/book/870

95. Nurdiana J, Franco-Garcia ML, Heldeweg MA. How shall we start? The importance of general indices for circular cities in indonesia. Sustainability 2021; 13(20):11168. https://www.mdpi.com/2071-1050/13/20/11168

96. Kantaratakul S. Localising the Circular Economy Concept under ASEAN Values [Internet]. SwitchAsia EU2025; Available from: https://switch-asia.eu/news/localising-the-circular-economy-concept-under-asean-values/

Glossary

Acoustic Sensors: Devices that detect and measure sound waves, converting them into electrical signals for various applications across multiple industries

Actuator System: A crucial component in automation and control, converting energy into motion to perform various tasks in mechanical systems

Acute Hepatopancreatic Necrosis Disease (AHPND): A fatal bacterial disease in shrimp is also known as Early Mortality Syndrome (EMS). It is caused by Vibrio parahaemolyticus (VpAHPND), which carries PirA and PirB toxins. AHPND attacks the shrimp's hepatopancreas, leading to mass mortalities, often within the first 30-35 days post-stocking. Clinical signs include a pale or atrophied hepatopancreas, an empty gut and lethargy. PCR can confirm the diagnosis.

Adaptive Data Rate (ADR): LoRaWAN mechanism that automatically adjusts data rate and transmit power to optimize power consumption.

Additive Links On-line Hawaii Area (ALOHA): A protocol or the simplest multiple access method where stations can send data at any time without coordination

Advanced Biofloc Technology (ABFT): An innovative and sustainable aquaculture system that leverages bio floc to treat nutrient-rich waste, provide natural feed and maintain water quality. Integrating biofloc with additional water treatment units facilitates intensive cultivation under controlled conditions, leading to high productivity.

Aeration Efficiency (AE): A key factor used to assess how effectively an aeration system adds oxygen to water and distributes it evenly throughout a pond or tank, thereby supporting the life of fish and other aquatic biota. This efficiency also relates to how well an aerator can minimize oxygen loss and maximize oxygen transfer into the water.

AI-Camera: A camera system that integrates artificial intelligence technologies to improve its performance and overall user experience. By leveraging machine learning algorithms, computer vision and other AI techniques, these cameras can recognize and process the visual information within a scene, enabling features such as object recognition, scene recognition, image enhancement, smart composition, facial recognition, video stabilization and more.

Alanine Aminotransferase (ALT): An enzyme linked to liver function, commonly used as a biochemical marker of hepatic stress or injury in fish and other aquatic animals.

Alpha Melanocyte Stimulating Hormone (α-MSH): A peptide hormone is involved in regulating pigmentation, stress response and immune function in fish. α-MSH plays a crucial role in physiological adaptations to the environment, including changes in body coloration and defense mechanisms against stressors.

Alternative Proteins: Non-traditional protein sources used in fish feed, such as vegetable proteins (soybeans, algae), insect proteins (black soldier fly larvae) and microbial proteins. The use of protein alternatives aims to reduce dependence on fishmeal and improve sustainability in aquaculture.

Ammonia (NH_3/NH_4^+): The decomposition of nitrogenous organic matter naturally generates a chemical compound with a pungent and distinct odor. Ammonia formation often includes the breakdown of metabolic excretions from biota and decaying uneaten feed in aquatic environments.

Ammonia Excretion: The process by which fish excrete ammonia as a byproduct of metabolism. Ammonia is toxic at high concentrations, so its removal or conversion to less harmful compounds is critical for water quality.

Ammonia-Oxidizing Bacteria (AOB): Chemoautotrophic bacteria responsible for the oxidation of ammonia (NH3) to nitrite (NO2 -), utilizing CO2 as a carbon source. Notable genera include Nitrosomonas sp., Nitrosospira sp. and Nitrosococcus sp.

Antibiotics: a type of antimicrobial substance active against bacteria.

Aquaculture Species: Fish species or aquatic organisms that are cultivated in aquaculture systems. Each species has unique nutritional and environmental needs, which influence management practices within RAS.

Aquaculture: The cultivation of aquatic organisms such as fish, crustaceans, mollusks and aquatic plants, under controlled conditions for commercial, recreational or resource management purposes.

Aquaponic RAS Technology: The combination technology of aquaponics systems and recirculation aquaculture systems.

Aquaponic: a food production system that couples fish with plants, whereby the nutrient-rich aquaculture water is fed to hydroponically grown plants. Plants are grown in hydroponics systems, with their roots immersed in the nutrient-rich effluent water. This enables them to filter out the ammonia that is toxic to the aquatic animals or its metabolites. After the water has passed through the hydroponic subsystem, it is cleaned and oxygenated and can return to the aquaculture vessels

Aquatic: Pertaining to water environments, including freshwater and marine systems; used to describe organisms, systems or processes that occur in or are related to water.

Artemia: Brine shrimp, commonly used as live feed in aquaculture, especially for young fish.

Artificial Intelligence (AI): The capability of to perform tasks typically associated with, such as learning, reasoning, problem-solving, perception and decision-making. It is a in that develops and studies methods and that enable machines to and use and to take actions that maximize their chances of achieving defined goals.

Aspartate Aminotransferase (AST): An enzyme involved in amino acid metabolism; elevated levels in fish blood or tissue may indicate liver or tissue damage caused by stress, toxins or disease.

Automated Adaptive Feeders: An automatic feeding system that adjusts the amount and time of feeding based on real-time data from sensors that monitor fish behavior and feed residues. This technology helps to minimize feed waste and improve efficiency.

Automated Feeding Systems: An automated feeding system that uses technology to feed fish based on programmed time or real-time data obtained from fish behavior and water quality. This system reduces feed wastage and improves feeding efficiency.

Benefit-Cost Ratio (BCR): A financial metric used to assess the cost-effectiveness of a project, calculated as the ratio of total benefits to total costs.

Biofilm: A layer of microorganisms, including nitrifying bacteria, that forms on the surface of filter media. This biofilm is crucial in biological filtration processes within aquaculture systems or water treatment, converting toxic compounds like ammonia into less harmful nitrates.

Biofilter: A component of RAS that hosts beneficial bacteria to convert toxic ammonia into less harmful nitrates.

Biofiltration: The biological filtration process uses microorganisms, such as nitrifying bacteria, to remove toxic substances such as ammonia and nitrites from the water. Biofiltration is essential in maintaining water quality in the RAS system.

Biofloc Technology (BFT): An aquaculture system that utilizes naturally formed communities of microorganisms (biofloc) within the pond. This biofloc serves a dual purpose: it processes organic waste (such as uneaten feed and feces) into protein rich biomass and it acts as an additional natural food source for the cultured fish or shrimp. This system typically employs minimal or even zero water exchange, making it efficient in water usage and potentially reducing feed costs.

Biological Filtration: A process in Recirculating Aquaculture Systems (RAS) where bacteria convert ammonia into less harmful compounds, ensuring water quality and supporting fish health.

Biometric Sensors: Specialized devices that convert biometric traits of individuals into electrical signals for identification and authentication purposes. They utilize unique physical or behavioral attributes, making them more secure than traditional methods like passwords or PINs.

Bixa orellana: (Annatto) A plant that is a natural source of carotenoid pigments. It is used as a shrimp feed additive to enhance the red or orange coloration of the shell and provides health benefits due to its antioxidant and antimicrobial properties.

Bluetooth: A short-range wireless technology standard that is used for exchanging data between fixed and mobile devices over short distances and building personal area networks. In the most widely used mode, transmission power is limited to 2.5 milliwatts, giving it a very short range of up to 10 metres. It employs UHF radio waves in the ISM bands, from 2.402 GHz to 2.48 GHz.

Broodstock: Mature fish used for breeding to produce offspring (seeds) in aquaculture.

Cannibalism: The phenomenon of one individual preying on another of the same species. Cannibalism often occurs in shrimp and barramundi aquaculture due to differences in size, high stocking density or insufficient feed, leading to significant survival losses.

Carboxyl: A functional group (-COOH) commonly found in organic acids, including humic substances, that contributes to their ability to chelate metal ions and influence pH and buffering capacity in water.

Circular Economy: An economic system aimed at minimizing waste and making the most of resources by reusing, recycling and regenerating materials in production.

Cloud: a paradigm for enabling network access to a scalable and elastic pool of shareable physical or virtual resources with self-service provisioning and administration on-demand

Condition Factor (CF): An index used in aquaculture to assess fish or shrimp's health, plumpness and wellbeing. It is calculated based on the relationship between an organism's weight and body length, reflecting how well it utilizes feed and adapts to its environment. A higher condition factor generally indicates better overall condition.

Conductivity: A measure of its ability to. The unit of conductivity is per meter (S/m).

Daily Feed Intake (DFI): The amount of feed consumed by an individual or group of fish within 24 hours. DFI is a crucial indicator for monitoring aquaculture growth performance, health and feed efficiency. Measuring DFI helps culturists optimize feeding practices and farm management.

Digestibility of Feed: The ability of the feed to be digested and absorbed by fish. A more digestible feed will reduce feed wastage and improve feed conversion efficiency, which is important for maintaining water quality in RAS.

Digestibility: The ability of fish to digest and absorb nutrients from feed. Feed with a high level of digestibility reduces feed waste and waste produced, as well as maintaining water quality in RAS.

Disease Management: Strategies used to monitor, prevent and treat diseases in aquaculture systems.

Disease: A deviation from the state of complete physical or social well-being of an organism involving a well-defined set of symptoms and etiology and leading to an impairment of its normal function. It may be inherited or caused by parasites, dietary deficiencies or by physical and chemical factors in the environment.

Dissolved Oxygen (DO): The concentration of oxygen in water, essential for fish respiration and survival; optimal levels are above 5–6 mg/L.

Downflow Hanging Sponge (DHS) reactor: This is an aerobic biofilter reactor used for water treatment in aquaculture. It consists of vertically hung sponge media through which water flows from top to bottom (downflow), allowing for the formation of a microbial biofilm. The reactor treats water by forming an efficient microbial biofilm that removes ammonia and organic matter, thereby improving water quality.

Edge Computing Devices: Hard ware components that process data closer to its source, enabling faster insights and reduced latency in various applications.

Electrochemical: Any process either caused or accompanied by the passage of an and involving in most cases the transfer of electrons between two substances—one a solid and the other a liquid.

Enterocytozoon hepatopenaei (EHP): A microsporidian parasite that infects the hepatopancreas of cultured shrimp. EHP causes hepatopancreatic microsporidiosis (HPM), characterized by stunted growth and significant size variation among shrimp. The HPM will lead to substantial economic losses, although it rarely causes mass mortality.

Ethoxyresorufin-O-deethylase (EROD): A biomarker enzyme used to measure the activity of cytochrome P450 1A, involved in the detoxification of organic pollutants in fish, often used in environmental monitoring.

Eutrophication: The process of excessive accumulation of nutrients, especially nitrogen and phosphorus, in water bodies, which can lead to a decrease in oxygen and water quality. In RAS, eutrophication can occur if feeding is not properly managed.

Extruded Feeds: Feed processed with extrusion technology to improve water stability, nutrient availability and digestibility. Usually, these feeds float and are suitable for fish species that require stable feed on the surface.

Feed Conversion Efficiency: A measure of how efficiently fish convert feed into body biomass. The higher the feed conversion efficiency, the less feed is needed to produce fish, which is beneficial for environmental sustainability and agricultural profits.

Feed Conversion Ratio (FCR): Feed conversion ratio, which is the ratio between the amount of feed given and the amount of fish biomass produced. Lower FCR values indicate better feed efficiency, which means fish can grow better with less feed amounts.

Feed Formulation: The process of making a balanced feed mixture for fish, paying attention to the nutritional content such as proteins, fats, carbohydrates, vitamins and minerals that suit the specific needs of each fish species.

Feed Monitoring Technologies: The technology is used to monitor fish feed consumption in real-time and evaluate feeding efficiency. The tool includes sensors that measure the amount of feed consumed by the fish and the rest of the feed in the system.

Feed Waste: Feed that is not eaten by the fish and collects at the bottom of the tank or decomposes. The disposal of this uneaten feed can lead to increased water pollution and a load on the biofiltration system.

Fixed Media Filters: Water treatment units use solid, stationary media (like gravel or plastic bio-balls) to attract nitrifying bacterial biofilms.

FLOCponics: A hybrid aquaponic system combining Biofloc and hydroponic techniques to enhance nutrient recycling and crop production.

Fluidized Bed Filters: Water treatment units in which the filter media (e.g., sand, garnet or plastic beads) are suspended by an upward water flow. Upward water flow maximizes the surface area for microbial biofilm to efficiently break down pollutants like ammonia and nitrite, making them highly effective for biological filtration in aquaculture systems.

Food Security: The condition in which people have regular access to sufficient, safe and nutritious food to maintain a healthy life.

Food-Producing Sector Globally: A vast and complex system encompassing agriculture, fisheries and aquaculture, which together provide the majority of the world's food supply.

Fulvic Acids: Low molecular weight, water-soluble fractions of humic substances that remain soluble across all pH ranges. They have a high capacity for chelating metals and enhancing nutrient absorption in aquatic organisms.

Functional Feeds: Specially formulated feed with additional active ingredients such as probiotics, enzymes or immunostimulants to improve fish health, improve feed efficiency and support water quality.

Gateway: A device that receives data from a LoRa end device and forwards it to a network server via the internet.

Global System for Mobile Communication (GSM): A digital cellular communication technology. GSM technology is widely applied to mobile communication devices, especially mobile phones. This technology utilizes microwaves and signal transmission that is divided based on time, so that the information signal sent will reach its destination. GSM is used as a global standard for cellular communication as well as the most widely used cellular technology in the world.

Grouper: A marine fish from the Serranidae family, subfamily Epinephelinae, which is found in tropical and subtropical waters. This fish has the characteristics of a stocky body, wide mouth, small scales, serrated operculum and serrated dorsal fin.

Hardware: A wide range of physical tools, equipment and devices used in various applications, including construction, DIY projects and technology.

Hepatosomatic Index (HSI): The ratio of liver weight to total body weight in fish, often used as an indicator of energy storage and fish health.

Humic Acids: Higher molecular weight components of humic substances that are soluble in alkaline solutions but precipitate in acidic conditions. Known for their ability to bind heavy metals and act as bioactive agents in aquatic systems.

Humic Substances: Naturally occurring organic materials resulting from the decomposition of plant and microbial matter. They include humic acids, fulvic acids and humin and play a key role in soil and water chemistry by influencing nutrient availability and metal binding.

Hybrid Biofloc-RAS: A system that combines biofloc technology with external RAS components to improve nitrification and provide extra nutrition for shrimp. This system can enhance both water quality management and feed efficiency.

Hydraulic Loading Rate (HLR): The media's water flow rate per unit surface area in a biofilter. HLR determines how quickly water passes through the biofilter, influencing the contact time between waste and microbial biofilm and, thus, pollutant removal efficiency.

Hypoxia: A condition of low oxygen levels in water, causing stress or mortality in fish.

Immune System: A complex network of cells, tissues, organs and substances that protects the body from infection and other diseases.

Immunostimulants: Substances that enhance the immune response of aquatic organisms, often added to feed or water to improve disease resistance and overall health in fish farming.

Integrated Agriculture-Aquaculture (IAA): A farming system that combines crop, livestock and aquaculture operations to optimize resource use and productivity.

Integrated Biofilters: Biofilters that combine sewage and plant bacteria to purify water in the RAS, remove harmful substances such as ammonia, nitrite and phosphate and support nutrient circulation in aquaculture ecosystems.

Integrated Multi-Trophic Aquaculture (IMTA): Sustainable aquaculture practices that involve the cultivation of several species of different trophic levels (e.g. fish, shrimp and algae) in one integrated system to optimize resource use and reduce waste.

Intensification: The increase of production in an aquacultural system through increasing the stock density (and expected production) in the existing water area.

Internal Rate of Return (IRR): The discount rate that makes the net present value (NPV) of an investment zero; a higher IRR indicates greater profitability.

Internet of Things (IoT): A network of physical devices embedded with sensors and software to collect and exchange data for real-time monitoring and control.

Lates calcarifer: Asian Sea Bass or barramundi, a fish species with high economic and nutritional value in aquaculture.

Listen Before Talk (LBT): An important technique in LoRaWAN communications to avoid interference and improve spectrum efficiency.

Litopenaeus vannamei: Also known as Pacific white shrimp, it is a dominant species in global shrimp farming due to its fast growth, adaptability to various salinity levels and high market demand.

Long Range (LoRa): Radio modulation technology for long distance communication with low power consumption.

Long Range Wireless Area Network (LoRaWAN): A network protocol that uses LoRa technology for IoT communications.

Long-Range Frequency Hopping Spread Spectrum (LR-FHSS): A new physical layer option that has been recently added to the LoRa family with the promise of achieving much higher network capacity than the previous versions of LoRa.

Low-Salinity RAS: A recirculating aquaculture system designed explicitly for culturing saltwater species, such as Pacific white shrimp (*Litopenaeus vannamei*), under low salinity conditions (salinity range of 5–15 ppt). This system recycles water efficiently and reduces the need for new water.

Melanin-Concentrating Hormone (MCH): This is a peptide hormone crucial in regulating fish's appetite, energy metabolism and pigmentation. In aquaculture, MCH influences fish growth and stress response, making it an area of research for optimizing feed and farm management.

Mergence of Gas: The process of gases from different galaxies or systems combining and interacting during a merger event.

Methanogenesis Bacteria: Anaerobic archaea that produce methane as a byproduct of their energy metabolism, i.e., catabolism. Methane production or methanogenesis, is the only biochemical pathway for ATP generation in methanogens.

Methemoglobinemia: A condition where nitrite binds to hemoglobin, reducing its oxygen-carrying capacity and leading to fish suffocation.

Microalgae: Microscopic algae used in RAS for biofiltration, nutrient cycling and oxygenation. Microalgae help maintain water quality by absorbing CO2 and excess nutrients and providing a food source for some species.

Microfinance Programs: Financial services (e.g., small loans) aimed at supporting small-scale farmers in adopting advanced technologies like RAS.

Micronano Bubbles (MNBs): A technology used for oxygenation with tiny gas bubbles, reaching nano scale sizes, in advanced RAS to maintain water quality.

Modular RAS Designs: Customizable, scalable RAS setups allowing gradual upgrades to suit farmers' budgets and space constraints.

Moina: A type of small freshwater crustacean used as live feed for larval and juvenile fish.

Moving Bed Bioreactor (MBBR): A biofilm based biofilter technology where microorganisms attach to freely moving carriers within a reactor, combining the benefits of activated sludge and fixed film systems.

Myostatin (MSTN): A natural protein that limits muscle growth in fish. Inhibiting MSTN can increase muscle mass and growth rate, resulting in larger cultured fish.

Neon Tetra (*Paracheirodon innesi*): A small, brightly colored freshwater fish native to the Amazon Basin, popular in the global ornamental fish trade.

Net Present Value (NPV): The difference between the present value of cash inflows and outflows over a period of time; a positive NPV indicates a profitable project.

Nitrate (NO_3^-): A less toxic compound that is the end product of the nitrification process.

Nitrification: a microbial process in the nitrogen cycle in which reduced nitrogen compounds, primarily ammonia, are converted to nitrite and then nitrate.

Nitrite (NO_2^-): An intermediate, toxic compound produced during the first stage of nitrification when ammonia is oxidized.

Nitrite-Oxidizing Bacteria (NOB): A group of autotrophic bacteria that play a role in oxidizing toxic nitrite (NO2-) into relatively harmless nitrate (NO3-). Examples of NOB include Nitrobacter and Nitrospira. NOB are essential in aquaculture biofilters to maintain water quality.

Nitrobacter: The nitrifying bacteria responsible for converting nitrites (NO2-) to nitrates (NO3-).

Nitrosomonas: The nitrifying bacteria responsible for converting ammomum (NH_4^+) to nitrites (NO2-).

Nursery Systems: The initial stage in aquaculture activities where fish or shrimp larvae/post larvae are reared in separate, controlled environments (e.g., small ponds, raceways or tanks) before being transferred to main grow-out ponds. Nursery systems aim to provide an optimal environment for early growth, reduce cannibalism, improve the survival rates of the young and allow for gradual adaptation to broader environmental conditions.

Nutrient Cycling: The process of recycling nutrients in an aquaculture system involves converting organic waste into a source of nutrients that are useful for plants or other organisms in the system, such as through the use of algae or plants in Integrated Multi-Trophic Aquaculture (IMTA).

Nutrient Loading: Accumulation of excess nutrients in the water that comes from uneaten feed and fish waste. This buildup can lead to a decrease in water quality, which has the potential to lead to eutrophication.

Nutritional Requirements: Fish nutritional needs include protein, carbohydrates, fats, vitamins and minerals. This need varies depending on the species of fish and its growth stage, as well as the environmental factors present within the RAS.

Oxygen Transfer Coefficient (kLa): A measure of the efficiency of an aeration system in transferring oxygen from the air into water. A higher kLa value indicates that the aeration system is more effective at dissolving oxygen, which is crucial for maintaining optimal dissolved oxygen (DO) levels for the health and growth of cultured aquatic organisms.

Oxygen Transfer Rate (OTR): The amount of oxygen transferred from the air to the water per unit of time. OTR is a critical measure of aeration effectiveness in aquaculture, ensuring sufficient dissolved oxygen (DO) availability for aquatic organisms and other biological processes.

Pathogens: Disease-causing microorganisms (e.g., Aeromonas, Pseudomonas, Vibrio) that threaten fish health in aquaculture.

Payback Period: The time it takes for an investment to break even in present value terms, considering the time value of money.

Pelletized Feeds: Feed is processed in the form of pellets, which can be submerged, slow-sinking or floating, depending on the type of fish and its food preferences. Pellets contain a mixture of nutrients that fish need and are designed to reduce wastage.

Phenolic Hydroxyl: A functional group (-OH attached to an aromatic ring) present in humic substances, contributing to antioxidant properties and redox behavior.

POKDAKAN (Kelompok Pembudidaya Ikan): Fish farmer groups in Indonesia that collaborate on production, marketing and resource management.

Precision Feeding: A feeding strategy that uses technology to measure the metabolic needs of fish in real-time and deliver the right amount of feed according to these needs. Precision feeding helps reduce feed waste and maximize the efficiency of fish growth.

Probiotics and Enzymes: Beneficial microorganisms (probiotics) and biological enzymes used in feed to improve digestion efficiency and nutrient absorption. Probiotics also support the gut health of fish, while enzymes help break down hard-to-digest feed components.

Probiotics: Beneficial bacteria (e.g., Bacillus, Lactobacillus) added to aquaculture systems to improve water quality and fish immunity.

Protein Efficiency Ratio (PER): An index used to evaluate protein quality in feed. PER is calculated based on the ratio of body weight gain (grams) per gram of protein consumed by fish or shrimp. A higher PER value indicates that the protein in the feed is utilized more efficiently for growth, making it an important parameter in aquaculture feed formulation.

Quinone: An aromatic compound with a ketone structure that plays a role in electron transfer and redox reactions within humic substances, influencing their oxidative and antimicrobial properties.

Quorum Sensing: A bacterial communication mechanism that regulates virulence factor expression, often linked to pathogenicity.

RASFF (Rapid Alert System for Food and Feed): A European Union system for sharing information on food and feed safety issues to ensure public health protection.

Recirculating Aquaculture Systems (RAS): An advanced land based farming technology that improves water quality control, a crucial factor for biota health and growth. It uses mechanical filtration, biofiltration and oxygenation units to create a biosecure environment.

Salinity: The saltiness or amount of dissolved in a body of, called (see also). It is usually measured in g/L or g/kg (grams of salt per liter/kilogram of water; the latter is dimensionless and equal to).

Server: that provides information to other computers called "" on a. This is called the. Servers can provide various functionalities, often called "services", such as sharing data or among multiple clients or performing for a client. A single server can serve multiple clients and a single client can use multiple servers. A client process may run on the same device or may connect over a network to a server on a different device. Typical servers are and.

Sinking Feeds: Submerged feed, usually used for fish species that prefer to feed at the bottom of ponds or tanks. This type of feed must be managed carefully to prevent the accumulation of residual feed that can damage water quality.

Smart sensors: Advanced devices that integrate sensing capabilities with processing and communication functions, enabling them to gather, analyze and transmit data efficiently.

Socio-Economic Impact: The effect of an activity or project on the social and economic well-being of a community or population.

Software: Computer programs that instruct the execution of a computer. Software also includes design documents and specifications.

Specific Growth Rate (SGR): A measure of the growth rate of fish over a specific period. It is a metric that quantifies the daily percentage increase in an organism's weight or biomass. It is a valuable tool for assessing growth performance and comparing the effectiveness of different treatments or conditions in fish farming.

Specific Surface Area (SSA): The total surface area of the filter media per unit volume influences the density of biofilm growth. The specific surface area (SSA) of biofilter media refers to the total surface area available for microbial colonization per unit volume or mass of the media. It is a crucial factor in determining the effectiveness of a biofilter because it dictates how much surface area is available for beneficial bacteria and other microorganisms to attach and perform their roles in waste removal.

Standard RAS: A baseline model of Recirculating Aquaculture Systems that includes conventional components like mechanical filtration, biofiltration, oxygenation units and water recirculation pumps. This system maintains water quality and creates a controlled and sustainable aquaculture environment.

Stocking Density: The number of aquatic animals kept per unit area or volume in a culture system; affects growth, health and water quality.

Submerged Biofilter: This is a type of biofilter where the media remains completely immersed in water. Microorganisms grow on the filter media to remove pollutants. These filters treat wastewater, improve water quality in aquaculture systems or remove contaminants from other water sources.

Sustainable Aquaculture: Aquaculture practices that aim to minimize environmental impact, optimize the use of resources (such as water and feed) and improve the well-being of aquatic species, while maintaining economic benefits.

Sustainable Business Model (SBM): A business strategy that creates long-term value by balancing environmental, social and economic goals.

Sustainable Fish Farming: The farming involves the cultivation of fish species in controlled environments, such as ponds, tanks etc.

Tandem Mariculture: A production system where species are spatially segregated to reduce direct competition and organic waste accumulation, leading to better water quality and higher yields than traditional polyculture.

Total Ammonia Nitrogen (TAN): The total amount of both ionized (NH_4^+) and un-ionized (NH_3) ammonia in the water.

Total Dissolved Solids (TDS): The total concentration of dissolved inorganic and organic substances in water, affecting water quality and fish health.

TOWS Matrix: A strategic planning tool used to develop strategies based on the analysis of internal (Strengths and Weaknesses) and external (Opportunities and Threats) factors.

Trickling Filters: These are biofilters in which water trickles over media that is not fully submerged, providing a large, porous surface area for biofilm growth and enhanced oxygen exposure.

Trypsin-to-Chymotrypsin (T/C) ratio: The ratio of the activity of two key digestive enzymes, trypsin and chymotrypsin, found in the digestive tract of fish and shrimp. The T/C ratio is a crucial indicator of nutritional status, feed digestive efficiency and gut health in cultured aquatic organisms. Changes in this ratio can suggest issues with nutrient absorption or a response to specific feed formulations.

Urbanization: The expansion of urban areas, leading to challenges like land scarcity and water pollution for aquaculture.

UV Sterilization: A water treatment method using ultraviolet light to kill or inactivate pathogens by damaging their DNA.

Volumetric TAN Removal Rate (VTR): A measure of a biofilter's performance in removing Total Ammonia Nitrogen from the water per unit volume of media per day. It measures how effectively a biofilter removes total ammonia nitrogen (TAN) from water, expressed as grams of TAN removed per cubic meter of biofilter media per day. It is a crucial metric for evaluating the performance and sizing of biofilters, especially in aquaculture and wastewater treatment systems.

Waste: In aquaculture, it usually refers to the effluent water that emanates from a farm unit. In integrated livestock-aquaculture: liquid and solid animal dejections.

Water Additive: A substance introduced into aquatic environments to enhance water quality, support fish health or promote system efficiency. Examples include probiotics, humic substances or chemical buffers.

Water Quality Parameters: Variables that affect water quality in RAS, including pH, temperature, dissolved oxygen levels, ammonia concentration, salinity and light. These parameters must be monitored continuously to maintain optimal conditions for fish health.

Water Quality: A critical factor in aquaculture; includes parameters like temperature, dissolved oxygen, pH, ammonia and salinity that influence health and growth.

Water Remediation: The process of removing contaminants or improving water quality through physical, chemical or biological methods, often employed in aquaculture and environmental restoration.

White Spot Syndrome Virus (WSSV): A highly contagious and lethal virus that infects crustaceans, particularly shrimp. WSSV belongs to the family Nimaviridae and genus Whispovirus and it is a large double-stranded DNA virus. This disease causes mass mortalities in cultured shrimp and can lead to significant economic losses.

Wireless Fidelity (Wifi): wireless network protocol used by computer devices to connect to the internet without using cables. The term WiFi itself is used to refer to a wireless LAN (Local Area Network) based on the IEEE 802.11 network protocol standard.

Wireless Sensor Network (WSN): network of spatially distributed sensors that monitor and collect data on physical or environmental conditions, enabling real-time data analysis and decision-making.

Zero Water Discharge RAS (ZWD-RAS): An aquaculture system designed to minimize or eliminate wastewater discharge into the environment. This is achieved by maximizing water reuse and processing solid waste for minimal discharge.

Zero-Water Exchange Recirculation System (ZWERS): A type of RAS where water is continuously recycled without replacement, reducing water usage and maintaining stable water quality.

ZigBee: An -based for a suite of high-level used to create with small, low-power, such as for, medical device data collection and other low-power low-bandwidth needs, designed for small scale projects which need wireless connection. Hence, Zigbee is a low-power, low-data-rate and close proximity (i.e., personal area).

About the Authors

Achmad Suhermanto, Completed his formal education in aquaculture, earning a Bachelor of Applied College (STP Jakarta), a Master's degree from Brawijaya University (UB Malang) and a Doctoral degree in Aquaculture science from Bogor Agricultural University (IPB Bogor). He currently serves as a lecturer at the Karawang Marine and Fisheries Polytechnic under the Ministry of Marine Affairs and Fisheries, teaching in the Diploma Program of Fish Farming. His research focuses on Aquaculture, fish vaccine and microbiology. Orcid ID:0000-0002-1274-0263 ; Scopus ID: 57193387867

Adam Robisalmi. The author is presently a young researcher at the National Research and Innovation Agency (BRIN) under the Research Center for Fisheries. He holds a Bachelor's degree in Aquaculture from Brawijaya University and a Master's degree in Biology from Padjadjaran University. His research focuses on aquaculture, particularly fish breeding. He has authored numerous articles on fish culture and breeding published in national and international journals, seminar proceedings and books. He was awarded as the fish breeder of the superior tilapia "Srikandi" in 2012 and in 2023 received an innovation award for the saline-tolerant tilapia "Srikandi" as part of the "114 Innovations of Indonesia – 2022" by the Business Innovation Center, Indonesia. Scopus ID: 57224173618; Orcid id: 0000-0001-5140-2681.

Agus Priyadi is a Principal Researcher at the Research Center for Marine and Inland Water Resources Conservation, National Research and Innovation Agency (BRIN), Indonesia. He holds a bachelor's degree in Biology from Universitas Nasional, completed in 1986. His expertise covers genetics and breeding, with a focus on domestication, breeding strategies and larval rearing of freshwater and ornamental fish species. Over the past five years, he has been involved in numerous research projects on endangered fish conservation, such as the domestication of *Betta channoides* and *N. notopterus*, as well as environmental DNA (eDNA) monitoring of threatened native species. He is also an author of several scientific publications in national and international journals and holds copyright on a scientific method for larval harvest in *Betta channoides*. Scopus ID: 36453937400

Ahmad Muzaki is currently working at the Research Center for Fishery, National Research and Innovation Agency (BRIN) as a junior researcher. Finished the bachelor's degree in Aquaculture from IPB University and a Master of Science in Aquaculture from Universiti Malaysia Terengganu. Since 2005, he has been involved in various research activities related to broodstock rearing and spawning, seed production technology, nursery and grow-out technology, particularly in marine culture fisheries. Several research articles have been published both domestically and abroad, focusing on aquaculture systems, environmental aspects of aquaculture, fish diseases and health and fish culture. He also actively participates in various national and international symposiums. Orcid ID: 0000-0001-9740-5044; Scopus ID: 57216152080

Alimuddin Paada is a lecturer at the Faculty of Agriculture, Al-Khairaat University. He earned his Bachelor's degree in Agronomy from Tadulako University and later completed both his Master's and Doctoral degrees in Agronomy at Bogor Agricultural University (IPB). His areas of expertise include plant ecophysiology, soil science and experimental design. His research has focused on the cultivation of soybean and sweet potato, as well as the effects of fertilizers and altitude on plant growth. Outside of his academic work, he is also actively involved in preparing Environmental Impact Assessments (AMDAL) and Strategic Environmental Studies (KLHS).

Asmanik is an associate engineer at Research Center for Marine and Land Bioindustry, National Research and Innovation Agency (BRIN), Indonesia. Graduated Bachelor's degree in Biology Education from Malang State University - Indonesia. Master's degree in Reproductive Biology and Doctorate in Fisheries and Marine Sciences were obtained from Brawijaya University - Indonesia. Research includes marine fish breeding and cultivation activities (grouper, snapper, cobia, pomfret and ornamental fish) and seaweed. Orcid ID: 0009-0009-0414-0805. Scopus ID: 57216153262.

Bambang Gunadi is a senior researcher at the Research Center for Freshwater Aquaculture, National Research and Innovation Agency (BRIN), Indonesia. He earned his Bachelor's and Doctoral degrees in Aquaculture from IPB University, Bogor (Indonesia) and his Master's degree from the Asian Institute of Technology (AIT), Thailand. His research focuses on aquaculture systems, water quality management and fish breeding. He has published numerous articles in scientific journals, books and other media and actively supervises students in several Indonesian universities. In 2006, he was awarded as the breeder of the superior striped catfish "Patin Pasupati" and in 2023 received the "114 Innovation of Indonesia - 2022" award for the saline tilapia "Srikandi". Orcid ID: 0000-0002-2912-6761; Scopus ID: 57217585215.

Bastiar Nur is a researcher at the Fisheries Research Center, National Research and Innovation Agency (BRIN), Indonesia. He holds a Bachelor's degree in Fisheries from Halu Oleo University and a Master's degree in Aquaculture Science from IPB University. His research interests encompass aquaculture, fish breeding, reproductive biology, fish physiology, fisheries resource conservation and aquaculture engineering and technology. He has contributed to numerous scientific publications in both peer-reviewed journals and conference proceedings within these areas of expertise. Orcid ID: 0009-0004-9207-0002; Scopus ID: 58766188100.

Dendy Mahabror is a Junior Researcher in Sustainable Aquaculture and Environmental Engineering Research Group at Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia. Graduated from the Environmental Engineering, Institut Teknologi Sepuluh Nopember-Surabaya, Indonesia, in 2004 and completed master's studies at Marine Science, The Open University, Indonesia, in 2018. Research interests focus on aquaculture and fisheries management in land and coastal, especially aquaculture monitoring technology, Recirculating Aquaculture System (RAS) and environmental engineering. Orcid ID: 0009-0004-1473-3843; Scopus ID: 56709637100.

Dewi Puspaningsih. The author is presently a junior researcher at the Research Center for Fisheries, National Research and Innovation Agency (BRIN). She holds a bachelor's degree in water resources management from Padjadjaran University and Master's and Doctoral degrees in Aquaculture Studies from IPB University. Her research focuses on water quality, sustainable aquaculture, environmental engineering, endemic species and natural live feed. She has been actively involved as a resource person in scientific activities, including guest lectures at various Indonesian universities and contributions to the Ministry of Marine Affairs and Fisheries as well as FAO programs on aquaponics. Scopus ID: 57203917376; Orcid id: 0009-0000-8089-2798.

Desak Gede Sri Andayani is a Senior Researcher in Environmental Nanotechnology Research Group at Research Center for Environmental and Clean Technology, National Research and Innovation Agency (BRIN), Indonesia. Graduated from the Chemical Engineering, National Development University (UPN) "Veteran" East Java, Indonesia, in 1993 and completed master's and doctor's studies at School of Pharmacy, Bandung Institute of Technology (ITB), West Java, Indonesia in 2004 and 2014. Research interests focus on improving the quality of water, soil and air using secondary metabolites in the form of bionanomaterials. Orcid ID: 0000-0002-6336-4384; Scopus ID: 55644799900.

Dody Dharmawan Trijuno is a Senior Lecturer at the Faculty of Marine Affairs and Fisheries, Hasanuddin University, Makassar, Indonesia. He obtained his Bachelor's degree at the Department of Fisheries, Faculty of Animal Sciences, Hasanuddin University, Makassar in 1987. He obtained his Master of Science degree from Tasmania University, Launceston, Australia in 1985 and completed his Dr. In the Faculty of Agriculture with a focus on Fish Physiology studies, Department of Applied Biological Sciences at Kyoto University, Kyoto, Japan in 2001. Since 1991, he has mentored 65 undergraduate students, 26 undergraduate students and 12 undergraduate students and is actively involved in various community service activities and research related to aquaculture commodities such as seaweed, catfish, grouper, crabs, shrimp, the environment with fish nutrition, resulting in the publication of various scientific works both nationally and internationally. Orcid ID: 0000-0001-7786-3507; Scopus ID: 6504470095.

Early Septiningsih is a Senior Researcher at the Research Center for Marine and Freshwater Resource Conservation, BRIN, Indonesia. She holds a Master's degree from the Faculty of Fisheries and Marine Sciences, Hasanuddin University. With over 20 years of experience, her research focuses on water quality management, sustainable aquaculture and mangrove conservation. She has contributed to interdisciplinary projects including anthropological toxicology and Integrated Multi-Trophic Aquaculture (IMTA). Early is an active contributor to national and international scientific forums and has collaborated with various universities and institutions. Orcid ID*: 0000-0003-4967-2169*.

Eddy Supriyono is a Professor at the Department of Aquaculture, Faculty of Fisheries and Marine Science, IPB University, Indonesia where he has served since 1989. He earned his Bachelor's degree in Aquaculture from IPB University in 1988. He completed his Master's degree in Aquatic Biosciences at the Tokyo University of Fisheries, Japan, in 1995 and continued his doctoral studies at the same university, which he completed in 1998. His academic and research interests are primarily focused on aquatic biosciences and physiology. Over the years, he has made significant contributions to the advancement of science through numerous patents and scientific publications at both national and international levels. Orcid ID: 0000-0003-3032-317X; Scopus: 56688550300.

Ediwarman is a senior researcher at the Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia. He received his Bachelor's and Master's degrees in Aquaculture from IPB University. His research focus includes fish nutrition and the development of environmentally friendly fish nutrition. Orcid ID 0009-0007-0023-5909 Scopus ID 59461458000.

Edy Barkat Kholidin is a senior Researcher in Research Center for Freshwater Aquaculture, Research Organization for Agriculture and Food – BRIN. He was born in Jakarta 2nd Oktober 1971. He started to work as a researcher at the Freshwater Aquaculture Development Center in Jambi. Ministry of Marine Affairs and Fisheries from 1997 to 2022. Since 2022, he has been a member of the Research Center for Fisheries – BRIN. His research has focused on freshwater aquaculture and fish diseases. Orcid ID: https://orcid.org/0000-0002-6385-7146 and Scopus id: 6503970991

Eko Setio Wibowo. Currently working at the Faculty of Biology, Jenderal Soedirman University as a Lecturer. He completed his undergraduate and master's degrees in Biology from Soedirman University. Several publications of articles related to aspects of biology and Physiology of Polycheta, Cultivation of Polycheta and aquaculture. Orcid ID: 0000-0002-1938-6260; Scopus ID: 57255877100

Eri Setiadi is a senior researcher at National Research and Innovation Agency (NRIA) Indonesia. He graduated from the Faculty of Biology at Nasional University Jakarta for a Bachelor of Science Degree and Master degree of Aquaculture at Kochi University, Japan. The research focuses on integrated aquaculture (aquaponics, IMTA, Rice-fish Farming), aquaculture engineering and toxicology. Scopus ID: 57203909195

Fajar Anggraeni. The author is presently a researcher at the National Agency for Research and Innovation's Fisheries Research Center. She holds a Bachelor's degree in Aquaculture from the Fisheries University of Jakarta and a Master's degree in Biology Studies from Padjadjaran University. Several research articles have been published on aquaculture, prawn reproduction, fish breeding and genetics. She is a member of the research group for fish domestication and breeding, currently working on whole genome sequencing of *Chitala* sp. and the identification of new local fish species from East

Kalimantan. Her innovation products include GI Macro II (Genetic Improvement of *Macrobrachium rosenbergii* II), officially recognized through the Decree of the Minister of Maritime Affairs and Fisheries Number 23/KEPMEN-KP/2014 as a superior strain in growth. Scopus ID: 57205466192; Orcid id: 0000-0003-2296-8699.

Goib Wiranto is a Research Professor in Electronics at Research Center for Electronics, National Research and Innovation Agency (BRIN). One of his researches is Sensor Development Based on Microelectronics Technology for Environmental Pollution Utilization. He is currently working on Microelectronics technology, one of which is used in the development of sensors to monitor water quality or environmental pollution such as rivers or water quality and also sensors for air pollution detection. Orcid ID: 0000-0002-2989-4779 ; Scopus ID: 6507827456.

Hessy Novita is a senior researcher at the Research Center for Veterinary Science, BRIN, in the Animal Aquatic Health Group. Her studies have focused on molecular, microbiology and characterization of aquatic pathogens with emphasis on infectious diseases of economically important freshwater marine fish in Indonesia. Her research has studied several pathogens in freshwater and marine fish and developed detection methods for the pathogens. She is also interested in developing diagnosis and alternative approaches for fish disease control in fish, e.g. immunostimulants, probiotics and vaccines. Orcid ID: 0000-0003-1394-6666; Scopus: 56856746400.

Hidayat Suryanto Suwoyo is a Senior Researcher in the Research Center for Fishery, Earth and Maritime Research Organization, National Research and Innovation Agency, Indonesia. He earned his Bachelor's degree in Aquaculture Study Program, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar in 1999. He obtained his Master's degree from Bogor Agricultural University in 2009 and completed his Ph.D. in Agricultural Science, Hasanuddin University, Makassar, in 2019. Since 2000, he has been actively involved in various research activities related to shrimp/fish aquaculture technology, aquaculture environmental management and silvo-aquaculture, resulting in the publication of numerous scientific papers both nationally and internationally. Orcid ID: 0000-0001-9530-5138; Scopus ID: 57216885829.

I Dewa Putu Hermida is a Senior Researcher in Sensors and Actuators Research Group at Research Center for Electronics, National Research and Innovation Agency (BRIN), Indonesia. Graduated from the Faculty of

Electrical Engineering, Adhi Tama Institute of Technology Surabaya (ITATS), Indonesia, in 1992 and completed a Master's Degree at the Institute Technology Bandung (ITB), in 2003. Research interests focus on microelectronics and thick-film technology, particularly in the design, fabrication and characterization of sensors. Orcid ID: 0000-0001-6020-1910, Scopus ID: 22634276100.

Idil Ardi is a Senior Researcher at the Research Center for Fisheries, National Research and Innovation Agency (BRIN), Indonesia. He earned his bachelor's degree in Fisheries Resource Utilization from Bung Hatta University, Padang, in 1995. He continued his master's studies in Marine Technology at IPB University and graduated in 2002. In 2012, he obtained his doctoral degree in Natural Resource and Environmental Management, also from IPB University. His research interests focus on aquaculture, particularly aquaculture environmental management for freshwater, marine, brackish water and ornamental fish commodities. He has published numerous scientific articles at both national and international levels. Scopus ID: 57203909744; Orcid ID: 0000-0002-8843-0579.

I Gusti Ngurah Permana is currently a researcher at the National Research and Innovation Agency, Fisheries Research Center, Government of the Republic of Indonesia. His research interests are focused on breeding and genetics of abalone and marine fish. Research in the field of molecular biology on abalone, Barramundi, grouper, red snapper and yellowfin tuna) Mitochondrial DNA analysis is used to study genetic diversity. He received intellectual property rights on a Probiotic composition for shrimp seed production based *on Bacillus cereus* BC bacteria and its culturing method. Methods and Tools for Abalone Farming in the Sea, Probiotic composition based on bacteria for maintenance of larvae and nursery of white snappers, *Lates calcarifer,* Composition and methods of probiotic culture based on bacteria for maintenance of yellowfin tuna larvae (*Thunnus albacares*). Several national and international articles have been published, focusing on mariculture, breeding and biotechnology. He also actively participates in national and international seminars Orcid ID: 0000-0001-9315-8875. Scopus ID: 58289934300

Iman Rusmana is a Professor of Environmental Microbiology at IPB University, Indonesia. He earned his Ph.D. from the University of Essex, UK, focusing on nitrous oxide production by nitrate-reducing bacteria, after completing his B.Sc. and M.Sc. in Microbiology at IPB. His research covers microbial ecology and molecular genetics related to nitrogen cycling, N_2O and methane emissions in tropical ecosystems and the development of bacterial probiotics for aquaculture. Prof. Rusmana has also consulted for the aquaculture industry and authored numerous scientific publications in microbial biotechnology and environmental microbiology. He can be identified in international research databases under Orcid ID: 0000-0002-6447-426X and Scopus ID: 8141544300.

Indra Pratama is a Junior Researcher in Freshwater Aquaculture Research Group at Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia. Graduated from the Faculty of Fisheries and Marine Sciences, Bogor Agricultural Institute, Indonesia, in 2003 and completed master's studies at School of Earth and Environmental Science, James Cook University, Australia, in 2014. Research interests focus on aquaculture and fisheries, especially fish reproductive biology, fish nutrition, fisheries ecology and aquaculture resources management. Orcid ID: 0000-0002-0668-1834; Scopus ID: 57213603529.

Irwan Jatmiko is a researcher at the Research Center for Fisheries, BRIN. He earned his master degree in the marine environment from the University of Tasmania. His research focuses on fisheries, with a particular interest in fish biology and management of pelagic species and their relationships to the marine environment. Orcid ID: 0000-0003-0046-8589; Scopus ID: 57195580363.

Isti Koesharyani is a senior researcher at the Research Center for Fisheries, BRIN. She earned her Bachelor's degree in Biology from Padjadjaran University. She has over 20 years of experience in fish health management and aquaculture, including collaborations with JICA, NACA, ACIAR and the Leibniz Institute in Germany. She has contributed to numerous research projects, seminars and the development of technical diagnostic guidelines for aquatic diseases under the Ministry of Maritime Affairs and Fisheries (KKP). Orcid ID: 0000-0002-1549-3173

Jojo Subagja is a senior researcher at Research Center for Applied Zoology-National Research and Innovation Agency. Work experience th. 1996-2000: as research partner of IRD-France European Union Project "Catfish Asia". Since 2000-2019: several domesticated native species have been released, including the jambal catfish in 2000, the mahseer fish (*Tor soro*). in 2011, the kissing gourami fish in 2016, the *C.carpio* fish "Rajadanu Super RD" in 2016 and the "wader-cakul" in 2019. Ongoing domestication research includes *Hemibagrus, Tor douronensis, Tor tambroides, Chitala sp* *and Wallago* fish. Nine books and more than 160 research papers have been published in national and international journals and proceedings. Orcid ID: 0000-0002-8998-2957; Scopus ID: 6505786565

Kukuh Adiyana is a senior researcher at the Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia. He earned his bachelor's degree in Environmental Engineering from the Sepuluh Nopember Institute of Technology (ITS) in 2004. He completed his Master's in Aquaculture Studies from IPB University in 2014. He is pursuing a doctoral degree in Aquaculture Studies at the same university. Since 2006, he has actively engaged in various research activities related to sustainable and environmentally friendly aquaculture, focusing on the development of appropriate aquaculture technologies. His research has resulted in several patents in aquaculture and has contributed to the development of sustainable aquaculture practices in Indonesia. Orcid ID: 0000-0003-2836-0609 ; Scopus ID: 57214676655

Kukuh Nirmala is a lecturer in the Department of Aquaculture, Faculty of Fisheries and Marine Science, IPB University, Indonesia. He earned his Bachelor's degree in Fisheries, with a major in soil science, in 1986. He obtained his Master's degree from Kyushu University, Japan, in 1993 and completed his Ph.D. at the same university in 1996. Since 1986, he has been actively involved in various research activities related to aquaculture environmental management, resulting in the publication of numerous scientific papers both nationally and internationally. Orcid ID: 0000-0001-8997-196X ; Scopus ID: 6603793667.

Lies Setijaningsih was born in Bogor, West Java, Indonesia on February 3rd, 1961. Finished bachelor's degree in fisheries department from University of Sam Ratulangi (UNSRAT) Manado in 1986 and completed the master's degree of aquaculture environmental at IPB University in 2009. Having experience as a lecturer in fisheries department at the University of Sam Ratulangi from 1986 – 1991 and more than 30 years being a researcher at the Agency for Marine Affairs and Fisheries Research. Currently, since June 2022, she has been working as senior researcher at the Research Centre for Fisheries, National Research and Innovation Agency (BRIN). From 1993 to 2021 has been involved in various research activities on inland water fisheries, fish nutrition and aquaculture especially on aquaculture engineering and technology. Some research articles have been published both domestically and abroad with focus on aquaculture systems, aquaculture environmental, fish culture and environmental engineering. The author also actively participates in various national and international seminars/symposiums. Orcid ID: https://orcid.org/0000-0001-6995-2841.

Lila Gardenia is a Senior Researcher at the Directorate of Scientific Collection Management, National Research and Innovation Agency (BRIN), Indonesia. She obtained her bachelor's and master's degrees from Bandung Institute of Technology and completed her doctoral studies at IPB University. Her research expertise lies in microbiology and aquaculture virology, with a focus on advancing scientific knowledge in aquatic disease management and microbial ecology. And also involved in scientific collection management to preserve and utilize biological resources (BioBank-BRIN). Orcid ID: 0000-0002-4535-2216 and Scopus ID: 57215434754.

Lolita Thesiana is a senior researcher at the Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia. She earned her bachelor's degree in Biology from Padjadjaran University in 2004 and a Master's in Environmental Engineering from the University of Indonesia in 2017. She is currently pursuing a doctoral degree in Aquaculture Studies at IPB University. Since 2005, she has been actively involved in various research projects focusing on sustainable aquaculture. Her work has led to the development of several patents and the publication of numerous scientific articles on sustainable aquaculture, both nationally and internationally. Orcid ID: 0000-0002-8827-9127. ; Scopus: 57214665660.

Mat Fahrur is a Young Researcher at the Research Center of the Fisheries, Earth and Maritime Research Organization, National Research and Innovation Agency, Indonesia. Obtained a bachelor's degree in Aquaculture Study Program, Faculty of Marine and Fisheries Sciences, Muslim University of Indonesia, Makassar in 2011. He obtained his master's degree from Hasanuddin University, Makassar in 2024. Since 2014, he has been actively involved in various research activities related to shrimp, fish, seaweed, fish and shrimp feed technology, as well as aquaculture environmental management which has resulted in the publication of various scientific papers both nationally and internationally. Orcid ID: 0000-0003-3708-4837; Scopus ID: 58442495800.

Moh Burhanuddin Mahmud is currently working at the Department of Aquaculture, Faculty of Fisheries and Marine Science, IPB University as a lecturer. He obtained both his Bachelor's and Master's degrees in Aquaculture from IPB University. His academic and research interests encompass a broad scope within the field of aquaculture, including water quality management, sustainable aquaculture systems, environmental engineering, phytoremediation utilizing Gracilaria as a bioagent, aquatic toxicity studies and spatial assessments for aquaculture development. He has actively participated in numerous scientific research initiatives and externally funded projects, notably as a member of the research team in the BIMA-funded program. Beyond his research endeavors, he has contributed to scientific discourse through oral presentations at various national and international seminars, including those hosted by IPB University. Orcid ID: 0009-0005-7423-8112;

Muhamad Yamin is a Senior Researcher at the Research Center for Fisheries, National Research and Innovation Agency (BRIN), Indonesia. He holds a doctoral degree and has extensive experience in the field of aquaculture and aquatic resource innovation. He earned his Bachelor's degree in Agronomy Faculty from Tadulako University and his Master's degree in Biotechnology from Bogor Agricultural University. His expertise includes recirculating aquaculture systems (RAS), fish and crustacean breeding (including gourami and crabs), integrated rice-fish farming, aquatic toxicology, aquatic plants culture and enzyme technology applications in aquaculture. His work supports national efforts toward sustainable aquaculture, improved fish health and eco-efficient farming systems. Orcid ID: 0000-0003-3910-1776. Scopus Author ID: 57200822946

Muhammad Hunaina Fariduddin Ath-thar is researcher at the Research Center for Applied Zoology, National Research and Innovation Agency (BRIN), Indonesia. Farid holds a bachelor's degree in Aquaculture from IPB University and a doctoral degree in Animal Breeding and Genomics from Wageningen University and Research, the Netherlands. Farid's research focuses on quantitative genetics, selective breeding and fish domestication for both food (aquaculture) and non-food (conservation) purposes. He has contributed to the development and release of several improved fish strains through selective breeding, including the BEST Nile tilapia (2009) and Rajadanu Super RD common carp (*Cyprinus carpio*) in 2016. His ongoing projects include the domestication of Hemibagrus nemurus and Tor spp., as well as whole genome sequencing of endemic fish species in Indonesia are supported by the National Research and Innovation Agency (BRIN), the Indonesia Endowment Fund for Education (LPDP), the YSDS Foundation, IGF–UGM and the Ministry of Education, Culture, Research and Technology. Orcid ID: 0000-0002-9071-4351; Scopus ID: 57207245820

Novita Panigoro is a senior researcher at the Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia. She received her Bachelor's degree in Aquaculture from Sam Ratulangi University. Her research focus includes fish nutrition and health management. Orcid ID: 0009-0007-3355-8034; Scopus ID 6504122688.

Nur Syafira Khoirunnisa is a junior researcher at the Research Center for Applied Microbiology, BRIN. She completed her Bachelor's in Bioprocess Engineering from Brawijaya University and obtained her Master's and Doctoral degrees in Soil Science and Environmental Biotechnology from IPB University. Her research interests include soil microbiology, bioremediation and microbial fuel cells, with presentations at various international conferences. Orcid ID: 0000-0003-2983-3762.

Otong Zenal Arifin was born in Ciamis on Desember 02, 1970. He studied the Bachelor's Degree at the Djuanda University, graduated in 1994. Master Degree were achieved at Bogor Agriculture University, graduated 2005. Current career as a Senior Researcher at Research Center for Applied Zoology, Research Organization for Life Sciences and Environment. National Research and Innovation Agency. Produced more than 100 scientific papers and other, both written alone or with other authors in the form of journals and proceedings, books and parts of books. Received an award in releasing newly domesticated fish species Takashi, Kissing gouramy fish in 2018, BEST *Nile tilapia* obtained throught selective breeding in 2009, Radjadanu, Cyprinid fish obtained through selective breeding in 2016 and Galunggung SUPER Giant Gorami obtained throught hibridization in 2018 from the Minister of Maritime Affairs and Fisheries. Orcid ID: 0000-0002-0243-7332; Scopus ID: 57203789129

Pamungkas Daud is a Senior Researcher in Radio Frequency (RF) Research Group at the Research Center for Telecommunication, National Research and Innovation Agency (BRIN), Indonesia. Graduated from the Faculty of Engineering, Institute Technology Bandung (ITB), in 1990 with a Doctorandes and earned an Engineering degree (ir.), at Institute Technology Bandung (ITB), in 1992. and completed Master's studies at the Faculty of Engineering, Institute Technology Bandung (ITB), in 2002. Research interests focus on Radio Frequency (RF), Microwave - Optic & Photonic. Orcid ID: 0009-0009-2022-8452; Scopus ID: 56964498800.**Puput Dani Prasetyo Adi** is a Senior Researcher in Communication and Signal Processing at the Research Center for Telecommunication, National Research and Innovation

Agency (BRIN), Indonesia. Graduate from the Faculty of Engineering, AKAKOM Yogyakarta, now Universitas Teknologi Digital Indonesia (UTDI), in 2008 and completed Master's studies at Faculty of Electrical Engineering, Focus on Control, Computer and Electronics Engineering, Hasanuddin University, Makassar, Indonesia, in 2013 and completed Doctoral studies at the Faculty of Computer Science and Electrical Engineering, Kanazawa University, Japan, in 2020. Research interests focus on Transmission Telecommunication, specifically on Long-Range Radio Frequency and Internet of Things. Orcid ID: 0000-0002-5402-8864; Scopus ID: 57212620847.

Rachman Syah is a Research Professor at the Fisheries Research Center, Earth and Maritime Research Organization, National Research and Innovation Agency. He obtained his Bachelor's degree in aquaculture from the Faculty of Animal Husbandry and Fisheries, Diponegoro University in 1985. He continued his postgraduate studies and obtained a Master's degree from Hasanuddin University in Environmental Management in 1986. He continued his doctoral studies at IPB University in the marine and coastal resource management study program and obtained his doctoral degree in 2004. Since 1986, he has been actively involved in brackish water aquaculture research activities at the Ministry of Marine Affairs and Fisheries, then switched to the National Research and Innovation Agency since 2022. Throughout his career as a researcher, he has produced scientific papers published in national and international journals. Scopus ID: 57188980633 ; Orcid ID: 0000-0001-8721-8157.

Rasidi Rasidi. Currently working at the Research Center for Fishery, National Research and Innovation Agency/BRIN as a senior researcher. I finished the bachelor's degree in biology from Soedirman University, Master of Biology Science from Indonesia University and the doctoral degree from IPB University majoring in Aquaculture Study. Currently, as resource persons for Riset dan Inovasi untuk Indonesia Maju (RIIM) competition project with the theme of humic substance as feed additive in aquaculture. Some national and international publication of scientific article related with the fish feed, sustainable and environmental aquaculture. Orcid ID: 0000-0002-6624-8434; Scopus ID: 57203913450.

Rendy Ginanjar is a junior researcher at the Research Center for Conservation of Marine and Inland Water Resources, part of Indonesia's National Research and Innovation Agency (BRIN). He holds a bachelor's degree in Aquaculture from Brawijaya University (2007) and a Master's degree in Aquatic Bioresources from the University of Montpellier 2, France (2013). Currently, he is pursuing a PhD in Aquatic Ecology and Fisheries Resources at Charles Sturt University, Australia. Since 2008, Rendy has been actively engaged in a range of research initiatives related to aquaculture and aquatic biodiversity. His contributions have resulted in several patents and numerous scientific publications on sustainable aquaculture and aquatic biodiversity at both national and international levels. Orcid ID: 0000-0001-7280-0216

Reza Samsudin is a junior researcher at the Research Center for Applied Zoology, National Research and Innovation Agency. He received his Bachelor's and Master's degrees in Aquaculture from IPB University. His research covers Major Programme of Aquaculture in including fish nutrition, feed technology, fish biology and physiology, Biochemistry, sustainable aquaculture, fish nutrition related with fish breeding, environment and fish health. Orcid ID: 0000-0002-0513-8549; Scopus: 57204550596

Riza Zulkarnain is a Junior Researcher in Sustainable Aquaculture and Environmental Engineering Research Group at Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia. Graduated from the Chemical Engineering, Institut Teknologi Sepuluh Nopember-Surabaya, Indonesia, in 2004 and completed master's studies at Chemical Engineering, Universitas Indonesia, Indonesia, in 2014. Research interests focus on aquaculture and fisheries, especially aquaculture technology, Recirculating Aquaculture System (RAS), environmental engineering. Orcid ID: 0000-0001-6250-6857; Scopus ID: 57214675984.

Ruby Vidia Kusumah is a researcher at the Research Center for Fishery, National Research and Innovation Agency - Indonesia (from 2022) and the Ministry of Maritime Affairs and Fisheries - Indonesia (2009-2022). In 2020, he graduated from IPB University with a Master of Science in aquaculture science. His scientific interests include aquaculture and fisheries, with a focus on fish domestication, breeding and genetics. Various national and international research collaboration projects have been carried out in the field of aquaculture and fisheries. In 2022, he is working on a project in Indonesia to domesticate the endangered fish balashark (*Balantiocheilos melanopterus*) and Notopterus notopterus. In addition, he is working on developing tools for detecting and monitoring endangered fish in Indonesia, DNA barcoding and whole genome sequencing to aid with fish domestication. International and national publications on fisheries and aquaculture have been published. Orcid ID: 0000-0003-4477-8482; Scopus ID: 36117980300

Sahabuddin is a senior researcher at the Fisheries Research Centre of the Indonesian National Research and Innovation Agency. He obtained his Bachelor's degree in Fisheries with a concentration in Fisheries Resource Management in 1996. He earned his Master's degree in 1996 and completed his doctoral programme in 2015, all from Hasanuddin University. Since 2005, he has been actively involved in various research activities related to Aquaculture Fisheries and aquatic cultivation technology, resulting in numerous scientific publications both nationally and internationally. Orcid ID: 0000-0002-5592-7829; Scopus ID: 57200532321.

Sri Suryo Sukoraharjo is a senior researcher at the Research Center for Fisheries, BRIN. He earned his doctoral degree in marine science from IPB University. His research focuses on applied oceanography, with a particular interest in the variability of ocean mass circulation and the application of oceanographic influences on the coastal marine environment, as well as their relationship to marine fisheries resources. Orcid ID: 0000-0001-8760-9705; Scopus ID: 57223101678.

Suhardi Atmoko Budi Susilo was born on June 23, 1983, in Malang, East Java. He completed his Bachelor of Chemistry at Brawijaya University in 2008. After working for 13 years at Directorate General of Aquaculture, Ministry of Marine Affairs and Fisheries (KKP), he currently serves as a junior engineer at the National Research and Innovation Agency (BRIN) under Research Center for Fishery. His current research focuses on aquaculture mainly on sustainable aquaculture and environmental engineering. Orcid ID: 0009-0003-7953-4637; Scopus ID: 58575635200.

Titin Kurniasih is a senior researcher at the Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia. She received her Bachelor’s degree in Aquaculture from Diponegoro University, her Master's and Doctoral degrees in Aquaculture from IPB University. Her research focus includes fish nutrition and the development of environmentally friendly fish nutrition. Orcid ID 0000-0002-1658-6048; Scopus ID 58713233600.

Tuti Wahyuni is a senior researcher at the National Research and Innovation Agency. Her expertise lies in marine natural products, with a focus on the bioactive compounds found in seaweed and fish byproducts. Her research examines the characteristics of seaweed and fish byproducts, aiming to develop them as natural ingredients for cosmeceuticals and nutraceuticals. Alongside her endeavors in marine-based cosmeceuticals and nutraceuticals, she has a keen interest in sustainable aquaculture of marine resources, including fish and shrimp, as part of a broader strategy to bolster the blue economy and integrate coastal resource management for the empowerment of coastal women. Orcid ID: 0000-0002-6871-4582; Scopus: 57218477235.

Tutik Kadarini is a distinguished principal researcher at the Research Center for Fishery, National Research and Innovation Agency (BRIN), Indonesia. She earned her D-4 Diploma in Aquaculture from the Fisheries University, Jakarta, in 1990, a Bachelor of Fisheries from Dr. Soetomo University, Surabaya, in 1991 and a Master's degree from the IPB University, Bogor, in 2009. Her research expertise lies in fish hatchery techniques, with a focus on rainbow fish and perot rainbow fish. She has authored two notable domestic collection books, "Rainbow Fish Hatchery Technique" and "Perot Rainbow Fish Hatchery Technique," and has written dozens of papers in scientific journals, proceedings and presentations at national and international seminars. With decades of experience, she continues to advance fishery research and innovation in Indonesia. Orcid ID: 0009-0000-9321-2464; Scopus: 57195980531

Wahyu Pamungkas. The author is presently a researcher at the National Agency for Research and Innovation's Fisheries Research Center. She holds a Bachelor's degree in Aquaculture from Brawijaya University, as well as Master's and Doctoral degrees in Aquaculture Studies from IPB University. Several research articles have been published on aquaculture, freshwater fish nutrition and reproduction, fish breeding and biofloc systems. Orcid ID: https://orcid.org/0000-0002-5450-6336. Scopus ID: 57212406522

Wahyulia Cahyanti is a graduate of Brawijaya University with a Bachelor's degree in Fisheries, while her Master's degree was obtained from IPB University. As a young researcher at the Research Center for Applied Zoology, National Research and Innovation Agency, the author has studied various aspects of aquatic fauna zootechnics, including the domestication of native Indonesian fish, reproduction and aquaculture technology. Orcid ID: 0009-0005-9599-0047; Scopus ID: 57222543946.

Waryat is a senior researcher at the Research Center for Agroindustry, National Research and Innovation Agency (BRIN) Indonesia. He received his Bachelor's degree in Faculty of Fisheries and Marine Science from

Diponegoro University, Master's Degree in Food Science and Technology from Gajah Mada University, Yogyakarta and Doctoral degrees in Agroindustry from IPB University. His research focuses on agricultural postharvest, with recent work actively examining the shelf life of agricultural products. Orcid ID 0000-0003-4167-9833; Scopus ID 57222182261.

Yani Aryati is a senior researcher at the Research Center for Applied Microbiology, National Research and Innovation Agency (BRIN), Indonesia. She holds a Bachelor's degree in Aquaculture from Gadjah Mada University, a Master's in Microbiology from the University of Indonesia and a Doctorate in Aquaculture from IPB University. Her research focuses on fish diseases, aquaculture and fish nutrition. She has actively contributed to scientific publications, conferences and guest lecturing in the field of aquaculture. Orcid ID: 0000-0001-6070-266X

Yuli Siti Fatma is a junior researcher at the Research Center for Applied Microbiology, BRIN. She received her Bachelor's degree in Biology and her Master's and Doctoral degrees in Microbiology from IPB University. Her research covers microbial ecology in aquatic and soil environments, including methane emissions, nitrogen cycling in aquaculture and microbial adaptations in saline and metal-contaminated soils. Orcid ID: 0000-0002-2651-3598.

Zainuddin is a Senior Lecturer at the Faculty of Marine Affairs and Fisheries, Hasanuddin University, Makassar, Indonesia. He obtained his Bachelor's degree at the Department of Fisheries, Faculty of Animal Husbandry, Hasanuddin University, Makassar in 1989. He obtained his Master of Science degree from Bogor Agricultural University in 1998 and completed his Dr. in Fisheries Science with a focus on Fish Nutrition, Hasanuddin University, Makassar, in 2008. Since 1991, he has mentored 65 undergraduate students, 26 undergraduate students and 12 undergraduate students and is actively involved in various community service activities and research related to aquaculture commodities such as seaweed, catfish, grouper, crabs, shrimp, the environment with fish nutrition, resulting in the publication of various scientific papers both nationally and internationally. Orcid ID: 0000-0001-6293-232X; Scopus ID: 58220583400

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