



# Re-Circulatory Aquaculture Systems: A Pathway to Sustainable Fish Farming

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**Authors' contributions**

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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## ABSTRACT

Recirculating Aquaculture Systems (RAS) represent a transformative approach to sustainable fish farming that offers a viable solution to meet the growing global demand for seafood while minimizing environmental impact. These closed-loop systems recirculate and reuse water, reducing water consumption by up to 99% compared to traditional aquaculture methods. RAS also mitigate the risk of disease transmission, escapement, and pollution by isolating farmed fish from natural populations and the surrounding environment. Technologically advanced RAS employ mechanical

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filtration, biological filtration, and disinfection processes to maintain optimal water quality for fish growth. This high level of control allows for the farming of a wide range of species, including predatory finfish, in locations far from coastal areas. Furthermore, the integration of aquaponics in RAS enables the production of high-quality vegetables and herbs using the nutrient-rich wastewater, creating a sustainable closed-loop system. Despite the higher initial investment required, RAS have demonstrated consistent profitability and the potential for significant returns. By promoting "in-sourcing" and creating local jobs, RAS can contribute to the economic development of communities while reducing the carbon footprint associated with international seafood trade. As the aquaculture industry continues to evolve, RAS are poised to play a crucial role in ensuring the long-term sustainability of fish farming. By combining technological advancements with environmental stewardship, RAS offer a promising pathway towards meeting the world's growing demand for seafood while preserving the health of our aquatic ecosystems.

**Keywords:** Fish; RAS; sustainability.

## 1. INTRODUCTION

Recirculatory Aquaculture Systems (RAS) are self-contained, intensive aquaculture systems that use a significant portion of the water more than once. In these systems, water from the fish tanks is filtered and cleaned before being reused, reducing the amount of water required for fish farming. The water is recycled continuously, with new water added only to account for evaporation, waste removal, and splash out [1]. RAS are an intensive approach to fish farming that utilizes minimum land area and water by recycling and reusing the culture water after filtration [2]. Instead of the traditional method of growing fish outdoors in open ponds and raceways, RAS rears fish in indoor tanks within a controlled environment [3,4,5,6]. The water in RAS is purified and recirculated continuously, with new water added only to make up for splash out, evaporation, and waste removal. The system components remove or convert the produced waste products, such as solid waste, ammonium, and CO<sub>2</sub>, into non-toxic products. The purified water is then saturated with oxygen and returned to the fish tanks [7]. RAS can be used for high-density culture of various fish species and can reach production levels of up to 500 tonnes per year in the same area as traditional methods that produce 2-10 tonnes per hectare. The technology is based on the use of mechanical and biological filters and can be used for any species grown in aquaculture [8].

RAS play a crucial role in sustainable aquaculture due to their numerous benefits over traditional open-water systems. RAS significantly reduce water consumption by recycling and treating water, conserving this precious resource and minimizing the environmental impact of aquaculture [2]. By recirculating water, RAS

minimize waste discharge and chemical usage, protecting water quality and ecosystems. RAS can be located anywhere, including urban areas, reducing transportation costs and carbon emissions associated with traditional aquaculture. RAS maintain high water quality through mechanical and biological filtration, disinfection, and strict operating protocols, ensuring healthy aquatic ecosystems [2]. Closed-loop systems like RAS eliminate the risk of disease transmission from farmed populations to wild populations, ensuring the long-term health of aquatic ecosystems. RAS achieve higher food conversion efficiencies and growth rates compared to traditional systems, making them more productive and cost-effective. RAS facilities can be established in local communities, creating jobs and increasing market access, while also catering to the locavore food movement [9]. RAS operate in controlled indoor environments, making them a viable adaptation strategy to climate change, which can impact traditional open-water aquaculture [2]. 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 [10]. 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. This review aims to provide a comprehensive understanding of RAS as a sustainable and efficient approach to fish farming that can help meet the increasing need for aquatic food production while addressing environmental concerns.

## 2. SYSTEM COMPONENTS

### 2.1 Water Treatment and Filtration

#### 2.1.1 Mechanical filtration

Mechanical filtration is a critical component of recirculating aquaculture systems (RAS) for removing solid waste and maintaining water quality. The most commonly used mechanical filter in RAS is the drum filter [11]. The filtered water enters the drum and water is filtered through the filter elements of the drum. The rotation of the drum causes the filtered solids to be removed by backwash sprays [12]. Drum filters are available in various sizes to handle different flow capacities, typically ranging from 8-750 l/sec. They are made from stainless steel and have filter screens ranging from 20-100 µm. Gentle removal of particles and ability to remove particles as small as 40-100 microns. Removal of uneaten feed, feces and other suspended solids. Mechanical filtration is the only practical solution for removing suspended organic matter from the outlet water of fish tanks in RAS [13]. It helps maintain water quality by removing waste products excreted by the fish.

#### 2.1.2 Biological filtration

The use of biological filters in recirculating aquaculture systems is a crucial component for maintaining water quality and reducing waste in these systems. Biofilters are used to maintain water quality in RAS by removing ammonia, nitrites, and dissolved organic solids, as well as adding oxygen and removing excess nitrogen and carbon dioxide [14]. Various types of biofilters are used in RAS, including rotating biological contactors (RBC), trickling filters, and fluidized bed filters. Each type of biofilter contains a solid support medium where microorganisms settle over time. Biofilters are home to different types of microorganisms, such as heterotrophic bacteria that utilize dissolved carbonaceous material as their food source, and chemotrophic bacteria like *Nitrosomonas* and *Nitrospira* that utilize ammonia and nitrite as food sources, respectively. Biofilter design and operation involve a multidisciplinary approach, combining mechanical engineering, microbial ecology, and aquaculture husbandry. Factors such as water flow rates, temperature, and pH affect the performance of biofilters. Biofilter efficiency is evaluated based on nitrification

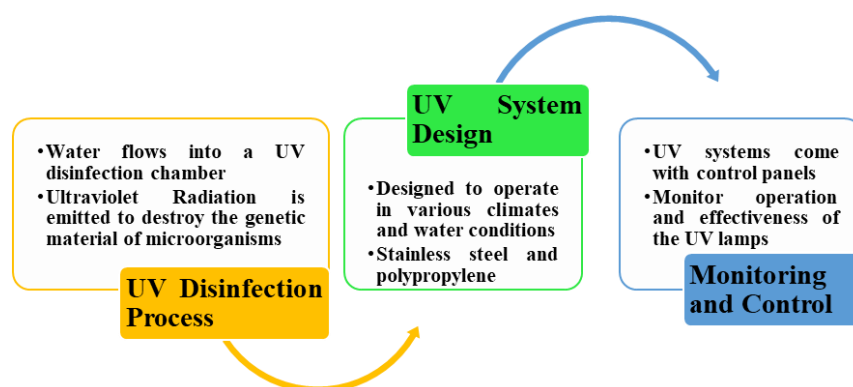
capacity, which is proportional to the total ammonia nitrogen (TAN) concentration. TAN levels must remain below 1.0 mg/l for optimal biofilter performance [15]. Biofilter performance can be hindered by microbial competition and interference, which can lead to reduced efficiency. Maintaining the health of RAS biofilters is crucial, and strategies such as pre-coating with nitrifying bacterial cultures and gentle periodic cleaning can help [16].

#### 2.1.3 Chemical filtration

The use of chemical filters in recirculating aquaculture systems is a crucial component for maintaining water quality and reducing waste in these systems. Chemical filters are used to remove dissolved solids, suspended particles, and other contaminants from the water in RAS. This helps to maintain optimal water quality for fish growth and health [11]. Various types of chemical filters are used in RAS, including drum filters, sedimentation filters, and moving bed filters. Each type of filter is designed to remove specific types of contaminants and has its own advantages and limitations. Chemical filters are designed to operate under specific conditions, such as water flow rates, temperature, and pH. Factors such as water quality, fish species, and system size influence the choice of filter type and design [17]. Chemical filter efficiency is evaluated based on the removal of suspended solids, dissolved organic matter, and other contaminants. The efficiency of chemical filters can be improved by optimizing operating conditions and regular maintenance [18]. Chemical filters are used globally in RAS for various aquaculture applications, including marine and freshwater species. The use of chemical filters is particularly important in RAS due to the high densities of fish and the need to minimize water exchange and waste generation [13].

#### 2.1.4 UV sterilization

UV sterilization is a widely used technology in recirculatory aquaculture systems globally (Fig. 1). It is applied as a supportive filtration method to biological and mechanical filters of biologically charged water, ensuring the highest water quality and fish health. UV sterilization is used in RAS facilities worldwide, particularly in fish farms and hatcheries, to maintain water quality and prevent disease outbreaks [19]. UV radiation targets and



**Fig. 1. The ultraviolet radiation disinfection process is used for water treatment and filtration**

inactivates microorganisms such as bacteria, viruses, fungi, yeasts, and algae, ensuring the water remains free of harmful pathogens. UV disinfection is a chemical-free method, which eliminates the risks associated with handling and dosing hazardous chemicals, and also minimizes the environmental impact of chemical disinfection methods [20]. UV sterilization helps maintain the physical and chemical composition of the water, ensuring optimal conditions for fish growth and health. UV systems are designed to accommodate high flow rates and provide full monitoring control, making them a cost-effective and sustainable choice for RAS facilities [21].

## 2.2 Oxygenation and Aeration

### 2.2.1 Aeration devices

Aeration devices play a vital role in recirculatory aquaculture systems by ensuring adequate oxygen levels for fish health and system efficiency.

### 2.2.2 Types of aeration devices

**Diffused Bubble Aeration.** This method involves providing low-pressure air from a blower to diffusers placed at the bottom of culture tanks. The diffusers release small air bubbles that rise through the water column, transferring oxygen efficiently to the water [22].

**Paddlewheels, Propeller Aspirators, and Vertical Lift Pumps.** These devices move water into contact with the atmosphere, enhancing oxygen transfer. However, they can create excessive turbulence in culture tanks, making diffused aeration more common for efficient oxygenation [23].

**Air Stones and Pipes.** These traditional aeration systems are commonly used in hatcheries and

culture tanks, producing larger air bubbles that rise quickly to the surface. While effective, they may not provide sufficient oxygen for high-density fish culture systems, leading to the preference for more efficient methods like diffused aeration or oxygen generators [24]. Maintaining adequate dissolved oxygen levels is essential for fish respiration, growth, and overall well-being. In RAS, where water is continuously reused, efficient aeration devices are vital to ensure optimal water quality and fish productivity [25].

### 2.2.3 Efficiency and Considerations

Studies have shown that diffused aeration systems can transfer oxygen at an average rate of 1.3 kg oxygen/kWh. However, this efficiency may vary based on factors like dissolved oxygen concentration, water temperature, and fish species requirements [26]. Properly sizing aeration devices is crucial to meet the oxygen demands of fish and biofilters. The oxygen consumption rate in a system is influenced by factors such as feed rate, waste removal efficiency, and fish density, necessitating careful consideration during system design [27].

## 2.3 Temperature Control

The worldwide overview of heating and cooling systems in recirculating aquaculture systems (RAS) involves the critical management of temperature to optimize fish growth and system efficiency. Heating and cooling are essential components in RAS to maintain the ideal temperature for fish, ensuring optimal growth rates and minimizing energy consumption [28]. In RAS, heating and cooling systems play a crucial role in maintaining water temperature within the specific range required for different species of fish. The use of heat exchangers, heat pumps,

and other technologies allows for efficient temperature control, contributing to the success of aquaculture operations. These systems are designed to provide a stable and controlled environment for fish, promoting growth and overall health [29]. The implementation of heating and cooling systems in RAS offers several advantages, including energy efficiency, precise temperature regulation, and the ability to adapt to varying environmental conditions. By utilizing heat pumps, air source or water source heat exchangers, RAS can optimize energy usage and reduce operational costs while ensuring the well-being of the aquatic species [30]. Overall, the global perspective on heating and cooling systems in recirculating aquaculture systems underscores the importance of technology and innovation in creating sustainable and efficient aquaculture practices worldwide. These systems not only support the growth of fish but also contribute to environmental sustainability by minimizing water consumption and energy usage in aquaculture operations [31].

## **2.4 Water Quality Monitoring**

### **2.4.1 Parameters monitored (pH, ammonia, nitrite, nitrate, etc.)**

A comprehensive overview of water quality monitoring in recirculating aquaculture systems (RAS) worldwide involves several key parameters, including pH, ammonia, nitrite, nitrate, and other essential indicators.

#### **2.4.2 pH and alkalinity**

pH is a critical parameter that expresses the intensity of the acidic or basic characteristics of water. In RAS, pH levels typically range from 6.5 to 8.5, with seawater generally having a pH of 8.0-8.5 and freshwater systems ranging from 6.5 to 9.0 [32]. Alkalinity is an important parameter that helps maintain pH stability. It is measured in terms of calcium carbonate ( $\text{CaCO}_3$ ) and typically ranges from 50 to 150 mg/L. Alkalinity helps neutralize acidic compounds and maintain a stable pH [32,33].

#### **2.4.3 Ammonia, nitrite, and nitrate**

Ammonia ( $\text{NH}_3$ ) is highly soluble in water and exists in two forms: un-ionized  $\text{NH}_3$  and ionized  $\text{NH}_4^+$ . The relative proportion of these forms depends on pH and temperature. Ammonia is toxic to fish and must be converted into less toxic forms through nitrification. Nitrite ( $\text{NO}_2^-$ ) is also

highly toxic to fish and must be converted into nitrate. Nitrite levels are mitigated by adding salt (chlorides) and decreasing pH. Nitrate ( $\text{NO}_3^-$ ) is the least toxic of the three and is non-toxic in freshwater systems. However, high levels of nitrate can still cause problems if not managed properly [32,33].

#### **2.4.4 Monitoring and management**

Monitoring water quality is crucial in RAS. Online monitoring systems, such as those provided by scan, help detect harmful levels of nitrite and nitrate immediately, allowing for prompt countermeasures to protect the fish [34]. Effective management involves regular monitoring of water quality parameters, including ammonia, nitrite, and nitrate. This helps ensure that the water quality remains within acceptable limits for the fish being cultured [33].

## **2.5 Waste Management**

Solid waste removal is a critical aspect of recirculating aquaculture systems to maintain water quality and fish health. The main sources of solid waste in RAS are uneaten feed and fish feces [35]. RAS typically remove solid waste through a combination of sedimentation and screen filters. Large settleable particles over 100 microns are removed by allowing the water to slow down in a sump tank, causing the particles to settle out. This process can be enhanced by running the water through tubes or over weirs in the settling tank [36]. However, sedimentation alone is not sufficient, as it only removes particles larger than 100 microns. To achieve adequate solids removal, particles down to 50-75 microns need to be removed. The most common equipment used for this are granular media filters and microscreens [37]. RAS can remove 85-98% of organic matter and suspended solids, and 65-96% of phosphorus through effective solid waste removal. However, the loosely aggregated fecal material and uneaten feed tend to break down into smaller particles, complicating the removal process. Biofloc technology (BFT) is also used in some RAS to help maintain water quality by promoting the growth of heterotrophic bacteria that consume ammonia and provide an additional food source for the fish [38].

## **3. SPECIES SUITABILITY**

### **3.1 Criteria for Species Selection**

The selection of fish species for recirculating aquaculture systems involves several key criteria

to ensure optimal performance and sustainability.

- Robust and fast growing species that can tolerate crowding and stress
- Warm water species like tilapia, catfish, barramundi, and rabbit fish are better suited than coldwater species like salmon and trout
- Species with well-known culture requirements, high demand, and viable economics
- Availability of fingerlings for grow-out nearly year-round
- Disease resistant species
- Species that can grow rapidly to a marketable size
- Freshwater species like tilapia, catfish, and carp are commonly grown in RAS.
- Marine species like barramundi, snapper, and rabbit fish are also suitable [31].

### 3.2 Fish species commonly cultured in RAS

The most commonly cultured fish species in recirculatory aquaculture systems are:

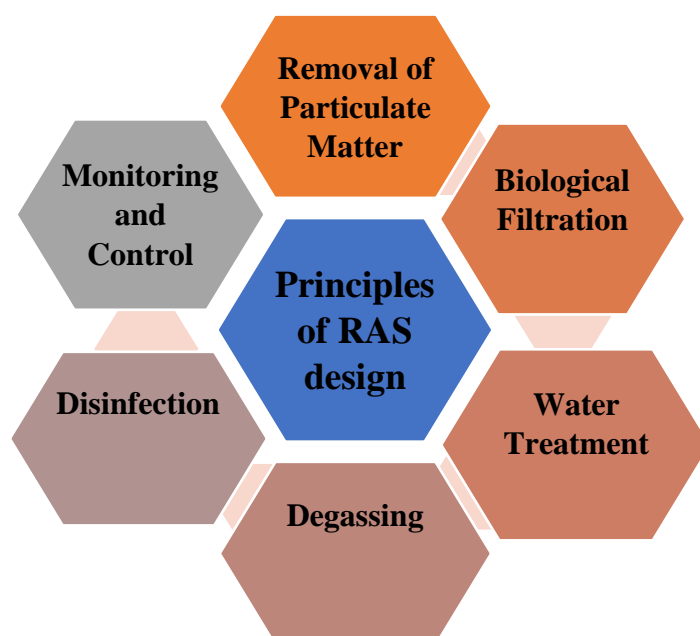
- Tilapia - Various species of this tropical cichlid are particularly well-suited to RAS due to their hardiness, ability to tolerate crowding and stress, and resistance to disease. Tilapia are substrate spawner and mouth brooders that grow rapidly [39].
- Catfish - Freshwater catfish species are commonly grown in RAS, especially in the United States. They have well-known culture requirements, high demand, and viable economics.
- Barramundi - This marine fish species is suitable for RAS and commonly cultured in warm water systems.
- Hybrid striped bass - The hybrid cross of striped bass and white bass tolerates freshwater and crowding in RAS well. It brings a higher price than tilapia.
- Carp - Various carp species are grown in RAS, especially in Asia where carp dominate global aquaculture production.

Other species like snapper, rabbit fish, yellow perch, and marine shrimp have also been successfully raised in RAS, but are less common. Coldwater species like salmon and trout are generally not well-suited to the warm, recycled water conditions in RAS. The choice of species depends on factors like culture requirements, market demand, availability of fingerlings, disease resistance, and ability to grow rapidly to marketable size in the RAS environment [40].

## 4. SYSTEM DESIGN AND LAYOUT

The principle of Recirculatory Aquaculture Systems is to filter and recycle water within a closed system to minimize water usage and environmental impact (Fig. 2). while enabling high-density fish farming [9]. In Table 1, basic components of RAS and maintenance frequency are described.

1. Water Recycling: The culture water is continuously purified and reused, with only a small percentage (typically less than 10%) replaced daily to make up for evaporation and waste removal [9]
2. Mechanical Filtration: Solid waste, such as fish feces and uneaten feed, is removed using mechanical filters like drum filters or sedimentation tanks.
3. Biological Filtration: Ammonia produced by fish is converted into less toxic nitrates by nitrifying bacteria in biofilters like biotowers or moving bed filters.
4. Oxygenation: The purified water is saturated with oxygen before being returned to the fish tanks [41].
5. Controlled Environment: RAS allows for precise control over water quality parameters like temperature, pH, and dissolved oxygen to optimize fish growth and health. By recirculating and treating the water, RAS can achieve water savings of up to 90% compared to traditional flow-through aquaculture systems. This makes RAS particularly suitable for areas with limited water resources or where environmental regulations require minimal wastewater discharge [23].



**Fig. 2. Basic principles of RAS design in aquaculture.**

**Table. 1. RAS Components and their maintenance.**

| Components             | Description   | Maintenance | Cost  |
|------------------------|---|-------------|-------|
| Biofilter              | Biological filtration unit to remove ammonia and nitrites | Monthly     | \$500 |
| Mechanical Filter      | Removes solid waste and particulate matter                | Weekly      | \$300 |
| UV Sterilizer          | Disinfects water by killing pathogens                     | Quarterly   | \$400 |
| Oxygen Generator       | Supplies oxygen to the water                              | Monthly     | \$800 |
| Water Pump             | Circulates water throughout the system                    | Bi-monthly  | \$600 |
| Temperature Controller | Maintains optimal water temperature                       | Monthly     | \$200 |

## 5. Operational Aspects

### 5.1 Feeding Strategies

Feeding strategies are crucial for the success of recirculating aquaculture systems. Proper feed selection is fundamental to fish health and financial performance in RAS. Feeds must satisfy all the minimum nutrient requirements for the cultured species, as there is little to no natural productivity in RAS tanks. Feeds should be low-pollution or "environmentally friendly" to minimize nutrient loading in the system [9]. Feed management is a key tool to improve feed utilization and reduce nutrient waste in RAS. Factors like feeding rate, frequency, and protein content affect the total ammonia nitrogen (TAN) added to the system, which determines the size and cost of filtration components. Using feeds with improved amino acid balance can enhance growth and reduce TAN loads [42]. Feeding

attractants, incitants, and stimulants can be used to improve feed utilization in RAS. Automatic feeding control methods using computer vision and neural networks are being developed to optimize feeding in dense RAS tanks [43]. Proper feeding practices, along with environmental conditions and disinfection methods, are critical influencing factors that must be controlled to ensure efficient and stable RAS operation [44]. Selecting the right feeds and feeding methods is an important aspect of fish growth and a fundamental part of indoor RAS.

### 5.2 Health and Disease Management

The health and disease management in recirculating aquaculture systems is a critical aspect of maintaining fish populations in such systems. These systems, also known as water reuse systems, are popular in aquaculture facilities, public aquaria, and tropical fish

wholesale operations. Proper management is essential to prevent disease outbreaks and ensure the well-being of the fish. Understanding species biology, nutrition, water quality, quarantine, sanitation, and disinfection are crucial for optimizing immune systems and reducing potential pathogens [45]. Knowledge of the anatomy, physiology, behavior, genetics, and environmental needs of cultured species is vital for proper management [45]. Implementing quarantine, sanitation, and disinfection protocols before introducing new fish into the system is essential to prevent disease spread [46]. Adherence to standard operating procedures, maintenance of water quality parameters, and strict recordkeeping are key to successful health management. Systems should be designed to manage unforeseen disease outbreaks, with provisions for isolating and treating affected fish populations. Efficient resolution of disease outbreaks requires thorough record examination, system evaluation, diagnostics, and collaboration with specialists [47].

### 5.3 Biosecurity Measures

Biosecurity measures in recirculating aquaculture systems (Fig. 3) are crucial for preventing the introduction and spread of infectious diseases. These measures aim to minimize the risk of

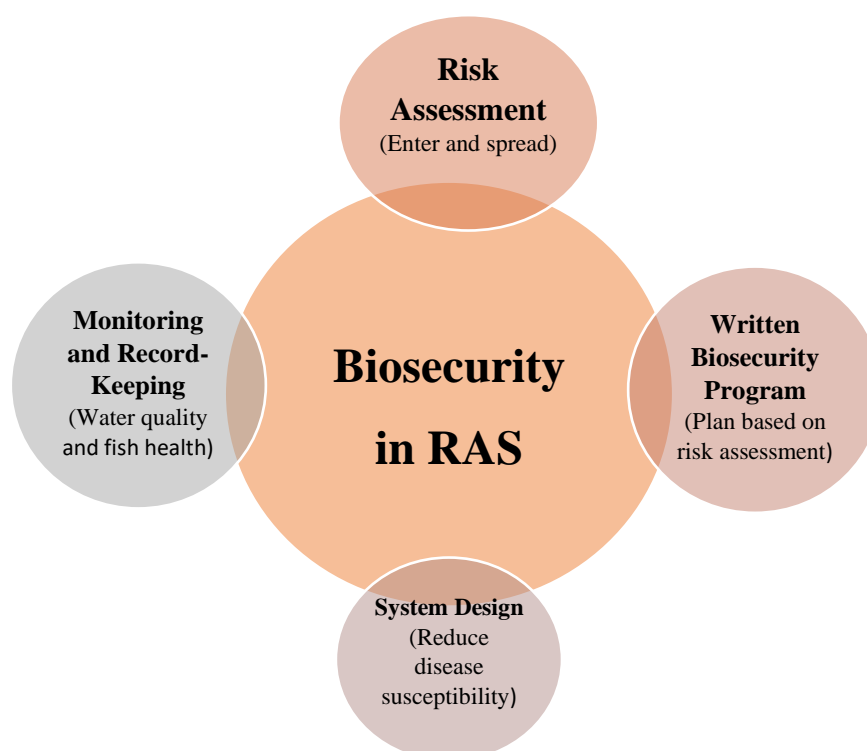
pathogens entering and spreading within aquaculture facilities. Key components of biosecurity in RAS include obtaining healthy stocks, managing pathogens, and educating staff and visitors.

- Animal Management: Obtaining healthy stocks and optimizing their health through good husbandry practices.
- Pathogen Management: Preventing, reducing, or eliminating pathogens to minimize disease risks.
- People Management: Educating and managing staff and visitors to ensure compliance with biosecurity protocols [45].

## 6. ECONOMIC CONSIDERATIONS

### 6.1 Initial Investment and Capital Costs

The initial investment and capital costs in recirculatory aquaculture systems vary globally. Initial investment costs per hectare for traditional systems range from \$64,500 to \$97,500, depending on farm size. For RAS, the average initial investment cost per hectare is perceived to



**Fig. 3. Biosecurity practices in recirculatory aquaculture system**



be \$279,500, \$333,600, and \$334,000 for small, medium, and large farms, respectively [48]. The detailed estimates for a recirculatory aquaculture system in India include a capital cost of ₹3,067,233 (approximately \$41,000 USD). The total project cost is ₹5,02,648 (approximately \$66,000 USD), with a profit of ₹1,122,000 (approximately \$15,000 USD) per tank. A study comparing land-based RAS with net-pen salmon production models highlights the significant upfront costs for RAS. The capital expense for a land-based RAS farm producing 3,300 metric tons of Atlantic salmon is approximately \$32 million USD, while a net-pen farm producing the same amount costs around \$12.3 million USD [49]. These costs reflect the significant investments required for setting up recirculatory aquaculture systems, particularly in comparison to traditional aquaculture methods.

## 6.2 Operating Costs

The operating costs of recirculatory aquaculture systems vary depending on several factors such as the type of fish being farmed, size of the operation, and location. Feed is the largest operating expense in RAS, accounting for 84-85% of total variable costs [48]. The cost of feed can range from \$1.96 to \$2.03 per kilogram of salmon produced. Electricity costs are significant, with an average cost of \$0.05 per kilowatt-hour (kWh). The total electricity consumption for a 3,300 metric ton (MT) RAS farm producing Atlantic salmon can be around 21.5 million watt-hours (MWh). Oxygen costs are relatively low, with an average cost of \$0.2 per kilogram of salmon produced. Bicarbonate costs are also relatively low, with an average cost of \$0.2 per kilogram of salmon produced. Labor costs are significant, with an average cost of \$0.33 per kilogram of salmon produced. Management costs are relatively low, with an average cost of \$0.16 per kilogram of salmon produced. Processing costs are significant, with an average cost of \$0.48 per kilogram of salmon produced [48].

## 6.3 Economic Viability and Profitability

The economic viability and profitability of RAS vary globally depending on factors such as the type of fish being farmed, local market conditions, and the efficiency of the system. A study found that implementing RAS in pangasius farming in Vietnam increased the net present value from an average of \$589,000 USD/ha to \$916,000 USD/ha for large farms. The probability of RAS being a profitable investment was found

to be 99% for both medium and large farms [48]. A case study on marine recirculating aquaculture systems (MRAS) in Trinidad and Tobago found that the system was technically and commercially feasible for producing high-quality shrimp. The study aimed to develop a profitability assessment model to evaluate the financial viability and sustainability of the system [50]. While RAS can be profitable, the overall economic viability of these systems depends on various factors such as the type of fish being farmed, local market conditions, and the efficiency of the system. A study noted that RAS models were not profitable when all costs were accounted for, but substantial increases in yields could make them more viable. The economic feasibility of RAS can vary across regions. For example, a study on African catfish aquaculture in Northern Germany found that RAS was a sustainable and economically profitable business due to additional benefits from further processing and product diversification [51].

## 7. CONCLUSION

The conclusion for a Recirculatory Aquaculture System emphasizes its significance in the future of aquaculture due to its numerous advantages. RAS allows for reduced water requirements, minimized land needs, flexibility in site selection, decreased wastewater effluent volume, enhanced biosecurity, and efficient environmental control. It enables high fish stocking densities, close monitoring of environmental conditions, and independence from weather fluctuations. However, implementing RAS requires a substantial upfront investment, high operating costs mainly due to electricity, and the need for skilled staff. Additionally, RAS has higher greenhouse gas emissions compared to non-recirculating aquaculture. Special types of RAS include Aquaponics, which combines fish and plants in a closed-loop system, and Aquariums used for display purposes with controlled water quality. Aquaponics offers the advantage of minimal waste generation and multiple crop harvests. Overall, RAS presents a promising approach to sustainable and intensive fish farming with careful consideration of its benefits and challenges. To discuss the challenges and opportunities for further development of RAS, including issues related to management, knowledge gaps, high investment costs, and the need for innovations like denitrification reactors and sludge management.

## DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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