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Beyond Sustainability: Recirculating Aquaculture System For Blue Revolution

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Abstract

Aquaculture, the science of raising aquatic life, offers a promising solution for sustainable food security. As humanity's appetite grapples with the twin challenge of safeguarding the environment and ensuring sustainable seafood production, it necessitates reassessing the sustainability of traditional aquaculture practices. Unlocking a paradigm shift towards traditional sustainable aquaculture practices like Recirculating Aquaculture Systems (RAS) offers a transformative solution, potentially redefining the ''Blue Revolution'' by promoting sustainability through water conservation. This review comprehensively analyzes RAS technology and delves into its historical progression, core principles, and diverse components of water treatment systems, rearing tanks, and biofiltration mechanisms. Additionally, the review explores successful applications for rearing diverse aquatic species and evaluates feed and disease management practices within the recirculating system. Current trends and technological advancements, including innovations in waste management, energy efficiency, and employment within this environmentally controlled system, are also highlighted. While acknowledging existing challenges in energy consumption, cost optimization, and feed sustainability, the review provides a comprehensive and critical analysis by emphasizing the immense future potential of RAS. The review aims to guide future research and development efforts by advocating environmentally friendly practices, paving the way for a more sustainable future for the resilient aquaculture industry.

Keywords: Recirculating Aquaculture Systems (RAS); Sustainability; Blue Revolution; Biofiltration; Water Conservation; Aquatic Species

Abbreviations

RAS: Recirculating Aquaculture Systems; PPP: Pathogens, Parasites, Pests; DO: Dissolved Oxygen; TAN: Total Ammonia Nitrogen; TSSs: Total Suspended Solids; VSSs: Volatile Suspended Solids; FCR: Feed Conversion Ratios; IPN: Infectious Pancreas Necrosis, BKD: Bacterial Kidney Disease; BOD: Biological Oxygen Demand; HRAPs: High-rate algal Ponds; PAS: Partitioned Aquaculture Systems; MBBRs: Moving Bed Biofilm Reactors; SND: Solids Nitrogen Denitrification; IMTA: Integrated Multi-Trophic Aquaculture; IAA: Integrated Aquaculture Agriculture systems.

Introduction

In recent decades, aquaculture has emerged as one of the fastest-growing agricultural sectors globally, offering significant sustenance opportunities for millions of individuals. Nonetheless, despite this remarkable progress, the current aquaculture production is unable to keep pace with the escalating demand for fish due to the rapid surge in the human population. Thus, implementing sustainable intensification methods is necessary to increase food production within the limited resource requirement. In this context, applying new innovative farming practices like the Recirculatory Aquaculture System (RAS) presents a novel approach to fish farming by providing environmental sustainability with limited resource utilization.

Recirculating Aquaculture System (RAS) is a highly productive, land-based, and water-efficient intensive farming system that offers an eco-friendly alternative to conventional fish production methods [1]. By continuously filtering, treating, and reusing water, RAS can control all environmental factors of production, resulting in maximized operational efficiency and minimized risks from Pathogens, parasites, pests (PPP), and climate change. As per NFDB [2], the Recirculating Aquaculture System (RAS) creates a new possibility for a high-density culture of diverse fish species by utilizing minimal water and land area. High production, water conservation, and biosecurity are the key features of this technology [3]. Recirculating Aquaculture Systems gain more attention from aquafarmers due to its ability to maintain stable and optimal water quality throughout the cultural period.

What is RAS?

A recirculating aquaculture system is a technology designed for culturing fish and various aquatic organisms. This system relies on a combination of mechanical and biological filters to effectively remove waste components from the water. After subsequent treatment, the purified water is recycled and reused to cultivate these organisms [4].

Due to its high production flexibility, precise control over environmental variables, and potential for year-round production, RAS is acknowledged as an eco-friendly and sustainable aquaculture practice [5]. At present, recirculation systems are considered a vital tool for advancing sustainable aquaculture because physicochemical water variables like pH, dissolved oxygen, temperature as well as alkalinity may remain more stable throughout the production cycle [6-8].

In contrast to conventional methods such as ponds, raceways, and cages, RAS operates with a lower water exchange rate and typically falls within the range from 0.1 to 3 m3 per kilogram of feed [9-11]. This innovative technology allows intensive practices with significantly high stocking densities to achieve maximum net production and substantial profits, far surpassing what can be accomplished through conventional open aquaculture systems such as ponds. In 1990s, a relatively small RAS could produce fish at a rate comparable to that of a much larger outdoor pond. A RAS facility covering 4.64 × 102 square meters has the capacity to produce an impressive 4.5 × 104 kilograms of fish [12]. This efficiency becomes apparent when comparing it to the special requirement of an 8-hectare outdoor pond to achieve an equivalent fish harvest.

Recirculating aquaculture systems encompass a culture unit intricately linked with a series of water treatment components, facilitating the reconditioned and reutilization of a portion of the water discharged from the culture unit and subsequently reintroduced into the same culture unit [13]. Managing wastewater discharge into the environment is a carefully controlled process that fosters the maintenance of ecological harmony. It optimizes water usage by reducing the volume of water per kilogram of fish production and upholds stringent biosecurity measures to ensure the overall health and well-being of aquatic species thriving in these high-density cultivation environments. Implementing a self-cleaning conditioning system and precise temperature control is imperative in achieving the exacting conditions for specific aquatic organisms' maximal growth and survival [14].

Nevertheless, the initial substantial capital required to establish Recirculating Aquaculture Systems (RAS) and the recurring operational costs associated with electricity, which are indispensable for maintaining water circulation and aeration, have limited its adoption among (peri-) urban farmers. The intricate nature of fish production technology imposes significant limitations on the widespread implementation of RAS in developing nations, specifically in sub-Saharan Africa [1,16]. The lack of trained personnel for managing water quality and rectifying mechanical malfunctions impeded the widespread adoption of RAS [16].

However, Recirculating Aquaculture Systems have the potential to achieve fish production levels 30–50 times greater fish yields per unit area compared to conventional fish farming techniques [3]. The economic feasibility of relevant parameters, such as ideal and maximum stocking densities, market pricing, energy expenditures, and more, often relies on approximations rather than precise data.

History of RAS

While still considered a relatively recent innovation, the Recirculating aquaculture system has roots dating back over 65 years. The first pioneering RAS research was carried out in Japan during the 1950s [17], primarily focused on designing biofilters for carp farming with limited water resources. By the late 1960s, RAS technology emerged in more tangible forms; noteworthy examples included Japanese static water aquaculture systems incorporating biological purification kits that utilized gravel as a medium and European packaged multistage water aquaculture systems (Wu et al. 2008). Despite significant advancements in water purification and microbiology purification in Japan during this era, the widespread adoption of RAS was hindered due to the formidable construction and operational costs, alongside the limited experience of farmers [17].

Meanwhile, Flow water aquaculture was the precursor of Recirculating Aquaculture Systems (RAS) in China, starting from land-based factory aquaculture, which emerged in the 1960s. This innovation commenced with a focus on industrialized fry rearing, initially using 'utility sheds + underground seawater.' Gradually, this approach expanded to encompass seawater fry rearing and aquaculture, culminating in the progressive sophistication of RAS systems [18,19].

The genesis of RAS research can be traced back to the 1980s when internationally advanced technologies served as references. For instance, China embarked on independent research and development efforts to adapt RAS equipment to its unique Chinese national conditions. Notable achievements from these endeavors include creating microscreen drum filters, ozone (O3) generators, and protein skimmers [19-21]. In recent years, China has further refined its RAS technologies. Key areas of improvement encompass materials for water purification, developing multifunctional solid-liquid separation devices, versatile protein separators, ultraviolet (UV) sterilizers, dissolved oxygen (DO) equipment, and enhancing water purification processes and technologies [22-24].

The expansion of RAS technology was particularly noteworthy in Europe and North America from the 1970s to the 1990s, with significant advancements, particularly in Germany and Nordic countries [1,25-27]. In the 1970s, a German venture successfully demonstrated the feasibility of extensive carp production within RAS, and this achievement marked a turning point in the history of Recirculating Aquaculture Systems (RAS). It also spurred further research and development by the Danish Aquaculture Institute in recirculating aquaculture systems, laying the foundation for fostering one of the initial commercial RAS industries, focusing on producing European eel (Anguilla anguilla) [28]. The Danish success catalyzed the subsequent development and adoption of RAS in other European nations during the late 1980s and 1990s [27]. Denmark also played a pivotal role in nurturing the concept of commercial fish production within RAS, leading to the construction of the first commercial RAS facility in 1980 [29].

Starting in the 1990s, Recirculatory Aquaculture Systems gradually began integrating advancements in biological engineering, microbial technology, membrane technology, and automation control for water purification. These innovations upgraded water purification, bottom discharge, oxygen content augmentation, and temperature control. Today, modern RASs have incorporated almost the entire comprehensive array of available water treatment techniques and state-of-the-art technologies in their systems [30]. As a pinnacle of modern intensive aquaculture, RAS offers year-round, high-density culturing regardless of seasonal fluctuations, water availability, or land limitations. Moreover, RASs also provide precise environmental control, ensuring optimal conditions for aquatic life.

The initial triumph of the RAS-based European eel industry inspired the development of RAS in North America [28]. Since the early 2000s, further advancements in RAS technology have continued to evolve and flourish in Europe, North America, Australia, and other aquaculture-producing countries like Australia [26,27,31,32].

Over the last four decades, Recirculating Aquaculture Systems (RAS), which encompasses aquaponics, have undergone substantial technological advancements [26]. In particular, the past two decades have significantly accelerated RAS technology, resulting in widespread adoption. Many developed countries have embraced RAS and supported RAS growth through policy frameworks, legislative measures, and substantial financial investments [23]. At present, countries at the forefront of recirculation aquaculture are actively engaged in comprehensive research endeavors. Their focus includes ecological engineering, enhancing water recirculation equipment, and developing corresponding mechanization and information technologies and facilities.

Basic Principles of RAS Operation

Recirculating Aquaculture Systems (RAS) represents a pioneering approach to fish farming that emphasizes maximum efficiency and eco-consciousness. These land-based, indoor fish-rearing facilities provide a controlled environment for fish stocking within specially designed tanks. The core principle underpinning RAS operation involves continuous water re-circulation through flow-through fish farms by diverting the water supply through ponds or tanks. This innovative approach not only optimizes water utilization but also focuses on treating the discharged water to eliminate detrimental fish metabolites. Consequently, RAS mitigates environmental impact, thus harmonizing the ecological balance and significantly reducing wastewater discharge levels. RAS's guiding ethos centers on enhancing water recycling efficiency and eliminating metabolic waste, ultimately fostering a harmonious and sustainable fish-rearing ecosystem.

Recirculating Aquaculture Systems (RAS) are known for their exceptional efficiency, with water reuse rates typically exceeding 90% [16,17]. They offer valuable opportunities for effective waste management, reduced water consumption, and nutrient recycling [17,27,33]. Water purification in RAS is accomplished through multiple techniques, including mechanical and biological filtration, sterilization, and oxygenation. A standard RAS configuration typically comprises solid removal mechanisms, biological filtration, and gas transfer systems. One critical step involves the utilization of biofilms in biofilters, where microorganisms play a vital role in removing ammonia and dissolved organic matter from the water.

In RAS, culture wastewater is laden with various particles, including residual feed and feces, as well as suspended particulates. These particles make up a substantial 80–90% of the total particulates by weight. Additionally, this wastewater also contains ammonia, nitrogen, nitrite, and a substantial population of bacteria [34]. Over time, complex microbial communities within RAS biofilms comprise diverse bacteria with various metabolic and physical properties. Specifically, nitrifying bacteria within the biofilter play a crucial role in converting toxic ammonia excreted by the fish into non-toxic nitrates through a two-step process.

The two-step conversion steps are carried out by distinct microorganisms, which can include archaea [35], bacteria [36], and a recently discovered organism referred to as comammox [37]. Typically, Nitrosomonas species are responsible for oxidizing ammonia to nitrite in marine RAS, while Nitrospira species often take on the task of subsequent oxidation and conversion of nitrite to nitrate [38,39]. Fish excrete nitrogen mainly as ammonia or ammonium [40]. In an aqueous solution, ammonia (NH3) is present as gaseous and cationic ammonium (NH4+), and their combined presence is quantified as total ammonia nitrogen (TAN). The production of TAN may increase if the amino acid profile in the fish feed is not well-balanced [41]. Thus, nitrification remains a pivotal process in the operation of Recirculating Aquaculture Systems because of the potential toxicity of these nitrogen byproducts [27].

A high organic load from solids can impede nitrification [42]. Solids can also serve as attachment sites for bacteria [43], leading to nutrient and organic matter leakage [44]. Solids and organic matter accumulation can create favorable conditions for sulfate-reducing bacteria, producing the highly toxic hydrogen sulfide (H2S) harmful to fish [45].

Notably, Nitrite can also be highly toxic to fish, with adverse effects on their survival observed at concentrations exceeding 1 mg L^{-1} [46]. However, fish generally tolerate higher nitrate concentrations. A typical RAS utilizes fixed-film bioreactors, where the nitrification process occurs within a biofilm attached to an artificial carrier media [47]. This configuration effectively manages ammonium and facilitates its conversion into less harmful nitrate within the aquaculture system.

In RAS, water use is highly efficient, employing a smaller water volume per kilogram of fish production. This approach implements higher biosecurity standards to ensure the overall well-being of aquatic species under intensive cultivation [14].

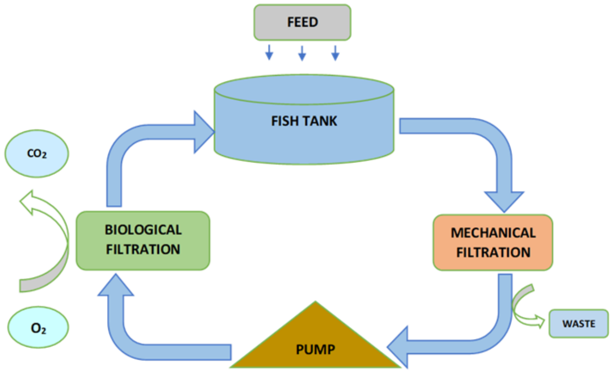

Figure 1: Schematic Representation of Recirculating Aquaculture System.

System Components of Recirculating Aquaculture System

A typical RAS facilitates highly efficient water reuse, exceeding 90%, with production tanks and a water treatment compartment. This ensures the maintenance of water quality, the removal or conversion of accumulated nutrients, organic matter, and particulates, as well as the control of nitrate levels [48-50].

The foundational system components of RAS technology revolve around some fundamental processes. A clarification process is employed to remove solids from the recirculating system. Following this, biofiltration is used to remove dissolved organics and ammonia, providing circulation between the tank and filtration components. After filtration, it is imperative to rebalance oxygen and carbon dioxide levels through aeration and degasification. These processes are paramount to the success of any RAS venture [51].

Comprehensive information regarding organic waste characteristics in recirculating systems is essential for effective equipment design capable of removing dissolved and fine organic wastes [52]. Thus, each step of the treatment process should be optimized to minimize the need for subsequent waste removal, thereby reducing the overall water exchange requirement [27].

Rearing Tanks - Water Circulation and Hydrodynamics

Recirculating Aquaculture Systems (RAS) are ingeniously crafted to efficiently cultivate substantial quantities of fish within relatively confined water volumes through the application of water treatment processes, such as the removal of toxic waste like ammonia and the subsequent recycling of the treated water [53]. The predominant utilization of tanks in RAS necessitates a relatively compact production area [54]. These systems can be tailored to raise a significant volume of fish within limited water resources space by effectively managing water quality and reuse strategies [55].

Essential tank characteristics for RAS encompass features such as self-cleaning capabilities, minimal particle retention time, efficient space utilization, and precise oxygen control. The success of fish rearing hinges on creating an optimal environment for fish in terms of water quality needs and tank design requirements. Factors like tank size, shape, water depth, and self-cleaning capabilities significantly influence species performance and stocking density [56,51]. Stocking density is purpose-dependent, with brood stocks typically kept at low density, while fingerlings, baitfish, and ornamental species require moderate stocking density. In contrast, grow-out fish can be raised at high densities [51]. The design of the rearing unit, whether tanks or raceways, aims to maximize the rearing volume relative to the available water flow.

The sizing of fish tanks is inherently linked to stocking density, with three prevalent tank shapes: circular, rectangular, and raceway configurations.

- **Circular Tanks**

In Recirculating Aquaculture Systems (RAS), circular tanks hold a dominant position and are primarily employed for fingerling and broodstock culture due to their innate structural and hydrodynamic advantages. Circular tank walls are inherently self-supporting under water pressure, allowing them to be constructed from lightweight polyethylene plastic or more robust fiberglass materials. The hydrodynamics of circular tanks facilitate the rapid removal of suspended solids, making them more efficient than other tank shapes. Circular tanks with sloping bottoms ensure consistent water quality, fostering optimal fish health and condition. Moreover, their center drains naturally enhance solids removal [51,57,55].

- **Rectangular Tanks**

On the flip side, rectangular tanks, while being approximately 20% more space-efficient, tend to struggle with solids movement, necessitating aeration systems to prevent water quality issues arising from waste particle accumulation on the tank floor. In specific industries, other tank shapes, like rectangular tanks with rounded corners, serve well, particularly in the ornamental fish, baitfish, soft crab, and tilapia sectors [51].

- **Raceway Tanks**

Raceway tanks, commonly employed in marine culture, are characterized by their controlled water circulation, making them a favored choice among tank options [56]. They offer a compromise by blending the self-cleaning benefits of circular tanks with efficient space utilization. However, this design involves the addition of a third wall along the tank's length to control water circulation, potentially increasing costs [51]. As the initial capital investment required for RAS systems is high compared to earthen ponds, the carrying capacity of the tanks becomes crucial to ensure cost-effective production [54].

Mechanical Filtration and Solids Management

In Recirculating Aquaculture Systems (RASs), wastewater carries a substantial load of residual feed, solid particulate matter, and excrement that necessitates early-stage removal for effective downstream water treatment processes. These solid particles originate from uneaten feed, fish waste, and bacterial activity, with commercial fish diets resulting in solid waste generation ranging from 25% to 50%. These solids exhibit a diverse size range, from larger settleable particles (>100 μm) to suspended particulate matter spanning from 100 to 1 μm in diameter. Without prompt removal, suspended particles can break down into smaller fractions, eventually transitioning into colloids and dissolved organic material (DOM) (1–0.001 μm) [58].

To further classify suspended matter based on sedimentation performance, which hinges largely on density and particle size. Particles with diameters between 1–100 μm, known as nonprecipitable Total Suspended Solids (TSSs), require removal through specialized equipment, and precipitable TSSs exceeding 100 μm can be more efficiently eliminated through solid-liquid separation equipment [43,60,61]. Organic matter within RASs includes volatile suspended solids (VSSs), which are vital in aquatic culture due to their involvement in oxygen consumption during organic compound degradation and potential involvement in biofouling issues [60]. In RASs, the swift removal of TSSs is paramount for maintaining water quality and system stability, particularly in light of stricter environmental regulations. Suspended solids, the primary aquaculture water pollutants, elevate BOD and oxygen consumption, potentially affecting fish health. Therefore, rapid solid waste elimination remains a core tenet of RAS management.

Typically, physical filtration methods such as sedimentation tanks (clarifiers), mechanical filters (granular or screens), or swirl separators are deployed to swiftly eliminate settleable solids, encompassing both inorganic (sand or coarse sand) and organic components (like feces and biological flocculation) [54].

Mechanical filters are essential for removing larger coarse impurities such as feces and leftover feed, while chemical filters, like charcoal, are particles beyond the capabilities of physical filtration. For recirculated fish farms, mechanical filtration proves to be the most practical method for efficiently eliminating organic waste from tank outlet water, which remains mechanical filtration. Typically, these systems employ microscreens equipped with filter cloths ranging from 40 to 100 microns [56]. Subsequently, the primary flow is directed to mechanical filters like drum or belt filters, effectively extracting suspended solids that are more prominent than the filter's mesh size. Due to their gentle particle removal design, drum filters are the most commonly used microscreen type. This process entails water entering the drum, passing through its filtered elements, and relying on the water level difference inside and outside the drum as the filtration driving force. Solids are trapped on the filter elements, lifted to the backwash area via drum rotation, and rejected organic matter is subsequently washed out into the sludge tray [56]. An experiment by Fernandes, et al. [58] demonstrated that micro-screen filtration significantly improved water quality compared to control groups. However, using a 20 μm mesh size did not yield a significant improvement relative to a 100 μm mesh size, potentially due to prolonged operation weakening the 20 μm mesh and causing cake formation.

Material filtration can also employ induced gravity methods, like swirl separators for denser particles, or screen filtration options like drum, belt, or matrix filters like sand filters [50]. The specific filtration size depends on the screen or matrix employed, with particles generally filtered to less than 40 μm.

Furthermore, various solid removal methods are available, including swirl separators, parabolic screen filters (PSFs), microscreen drum filters, and foam fractionators. Screen filtration is often inadequate for smaller particulates, such as bacteria, viruses, and colloidal organic matter (ranging from 10 to 0.001 μm), necessitating foam fractionation to trap organic material within foam [58]. Foam fractionators, also referred to as protein skimmers, are employed to address suspended solids that cannot settle at the bottom and may obstruct fish gill function and elevate oxygen demand. These devices also aid in controlling foaming agents that can accumulate in systems with extended water reuse [54,51].

In certain systems, a combination of different filters, such as screened sedimentation, up-flow sand, and plastic bead filters, for effective mechanical filtration. These compounds are often challenging to remove, potentially resulting in reduced water quality and heightened biofouling. In specific recirculating systems, a double drain system effectively eliminates settable particles from fish tanks, ensuring that a highly concentrated flow removes most particles while maintaining a low-solids main flow. Following mechanical filtration, the water proceeds to the biofilter for further treatment.

Biological Water Treatment

Biological purification stands as the central process within RASs, involving the critical selection of a biological medium and the cultivation of a biological membrane, primarily aimed at removing even the most minuscule particles. The pivotal components in this process are biofilters, which act as proficient processors of nitrogen compounds in water, encompassing bio-balls and bio-rings. Their paramount function is maintaining favorable water conditions for larvae and juveniles by effectively reducing ammonia concentrations [62,63]. Furthermore, they also contribute to effectively eliminating dissolved organic matter [51].

Ammonia nitrogen and nitrite nitrogen represent the primary metabolic wastes generated by residual feeds and excrement in RASs [64,65]. Fish excrete ammonia, containing urea, through their gills, and even low concentrations of the un-ionized ammonia form ($NH3$) can be toxic to fish. Fish safety necessitates the conversion of nitrogen into harmless nitrate within the biofilter. Bacteria thriving in recirculation systems, often associated with filter media, play a crucial role in converting harmful compounds (ammonia and nitrite) into fish-friendly nitrate [63]. Research has consistently shown that adding nitrifying bacterial products to the system can significantly enhance nitrification efficiency, reducing ammonia and nitrite levels and increasing nitrate levels [66]. In most systems, nitrification is indispensable for eliminating ammonia and nitrite from the water.

Meanwhile, heterotrophic bacteria oxidize organic matter, consume oxygen, and generate carbon dioxide, ammonia, and sludge. The bacterial consortia responsible for nitrosification and nitrification processes are complex and not yet fully understood. However, they generally encompass species like Nitrosomonas sp. Nitrosococcus sp. and Nitrospira sp. for nitrosification and Nitrobacter sp. for nitrification. These species exhibit different pH optima, with nitrosifying bacteria thriving at approximately pH 8 and nitrifying bacteria at pH 8.5 [67,68]. Moreover, the optimal temperature range for these bacterial communities falls between 28 to 37°C [68].

Nitrification results in the following reactions:
1. NH_4 (ammonium) + 1.5 $O_2 \rightarrow NO_2$ (nitrite) + H_2O + 2H+ + 2e
2. NO_2 (nitrite) + 0.5 $O_2 \rightarrow NO_3$ (nitrate) + e
3. $NH_4 + 2\ O_2 \leftrightarrow NO_3 + H_2O$ + 2H+

The presence of ammonia (NH_3) and its ionized form, ammonium (NH4+), is pH and temperature-dependent, collectively referred to as total ammonia nitrogen (TAN). Biological filtration, whether aerobic or anaerobic, relies on direct contact with microorganisms and wastewater to decompose and absorb TAN and nitrite nitrogen, thus enhancing water quality. Notably, when the pH level is low, ammonia in water predominantly exists in its less toxic, ionized form. However, even a slight pH increase, such as going from 6.5 to 7.5, elevates the concentration of toxic un-ionized ammonia by a factor of 10, underscoring the critical role of pH and temperature in managing total ammonia nitrogen (TAN). To ensure an optimal water quality environment, TAN and non-ionic ammonia levels should not exceed 1 and 0.05 mg L^{-1}, respectively, and in cold aquaculture systems, they should be maintained at 0.1–0.5 and 0.1–0.3 mg L^{-1}, is advisable [69]. The effectiveness of biological filters hinges on their capacity to accommodate bacterial populations. Thus, comprehending and regulating the nitrification process in recirculating aquaculture systems can significantly enhance production, reduce wastewater discharge, and bolster profitability for system owners and managers [70].

The biological filter converts ammonium into nitrite and subsequently into nitrate through oxidative reactions. Heterotrophic bacteria, utilizing organic carbon sources from suspended and dissolved solid wastes, have the potential to outcompete and even replace nitrifying bacteria, leading to a reduction in the nitrification rate by approximately 60%–70% [71,50]. Consequently, it is imperative to maintain low levels of organic material entering the biofilter. The effectiveness of biofiltration primarily hinges on maintaining pH levels and controlling water temperature within the system. To achieve satisfactory nitrification rates, it's crucial to keep water temperatures in the range of 10 to 35°C (with the most favorable range around 30°C) and pH levels between 7 and 8 [56].

The biofilter plays a critical role in eliminating solid waste through bacterial processes. Its primary purpose is to eliminate dissolved organic materials excreted by aquatic organisms, including sugars, starches, fats, and proteins. The nitrification process involves the conversion of toxic ammonia into non-toxic nitrate, which is facilitated by bacteria cultured on the filters in suspension or fixed-film (Biofilm) attached forms.

The efficiency of nitrification in a system hinges on the formation of biofilm. Biofilm on biofilters serves as sites of bacterial attachment, enduring various flow rates and water qualities while retaining their natural waste-processing abilities [47]. One of the key advantages of biofilm formation is its protective role, shielding adverse environmental conditions and immune defenses [72]. Bacterial communities responsible for this process tend to establish stable and effective biofilms on suitable substrates, ensuring a consistent nitrification process under specific fish stocking densities and ammonium loads in the system. The specific surface area indicates the surface required for biofilm growth and ensures uniform water flow, considering dead zones and channels in the system. Biofilms can be found in various materials used in RAS, including fiberglass, plastic, PVC, glass, stainless steel, rubber, aluminum, foam, and cement [72]. Commonly used biological filters include Submerged fixed beds, Trickling fixed beds, moving-bed biofilters, fixed-bed biofilters, and Rotating biological contactors (RBC).

Water Quality Control and Conditioning

Golz [73] conducted a study revealing that when exposed to their own waste, fish face the imminent risk of toxicity. Consequently, water quality is pivotal in providing an ideal growth environment for the desired fish species. To ensure the fish reaches market size, all production systems must maintain optimal levels of key water quality parameters, including dissolved oxygen, un-ionized ammonia-nitrogen, nitrite-nitrogen, and CO_2 concentrations [54]. Environmental factors, including water temperature, total ammonia nitrogen (TAN), dissolved oxygen, and nitrite-nitrogen (NO_2–N), have a substantial influence on the feeding behavior of fish [74-76]. Inadequate makeup water, leading to a reduction in system flushing, can deteriorate water quality [77,78]. A recirculating aquaculture system (RAS) emerges as a favorable solution, offering consistent and improved environmental conditions for fish health year-round, contributing to reduced feed conversion ratios (FCR) and enhanced feeding efficiency [79].

The assessment of water quality issues proves intricate due to their multifaceted origins, encompassing suboptimal system management and deficient system maintenance [16]. Furthermore, the effect of RAS showed significant results on various water quality parameters such as pH, Water temperature, dissolved oxygen (DO), Total Suspended Solids (TSS), and Total Ammonium Nitrogen (TAN), which yielded significant and noteworthy.

- **Ph**

Maintaining an appropriate pH level is of utmost importance in aquaculture systems [63]. The pH value profoundly influences crucial biochemical processes within the water, notably affecting the nitrification process, which is compromised at lower pH levels. In these systems, pH tends to decrease due to bacterial acid production and the generation of carbon dioxide by fish [80]. Consequently, it is imperative to consistently regulate both pH and water temperature at deemed acceptable levels, ensuring the continuity of the nitrification process within the water.

Upon release into the water, Phosphorus tends to exit predominantly through RAS effluents, escaping effective utilization by the system [81]. In this context, the central objective of a Recirculating Aquaculture System (RAS) revolves around the management of unionized ammonia-nitrogen (NH_3-N) concentrations within the culture tank [82]. It merits attention that abrupt pH fluctuations can subject cultured animals to stress, particularly fish, which exhibit diminished tolerance to pH extremes, especially at higher temperatures. The pH range in water is a critical parameter that cannot be overstated, given its role in processes like nitrification and its direct correlation with promoting optimal fish health. Moreover, pH fluctuations govern the conversion of ammonia into its less toxic ammonium form with decreasing pH and the conversion of ammonium into the more toxic ammonia form at higher pH levels, making ammonia toxicity an increasingly pertinent concern in instances of elevated pH.

- **Water Temperature**

The significance of water temperature on fish development and growth rates is unrivaled by any other parameter, making it a critical factor to consider. Fluctuations in temperature pose difficulties in fish consuming feed as they struggle to adapt to wide-ranging changes. It's imperative to recognize that each fish species possesses a specific temperature tolerance range. A study by Roncarati et al. [83] delved into this matter by assessing the growth performance and survival of the common catfish, *Ameiurus melas.* Elevating water temperature by 10°C results in a doubling of an organism's metabolic rate, subsequently leading to increased food consumption, accelerated growth rates, and amplified biological oxygen demand (BOD). David [84] investigated this relationship by studying the European catfish Silurus glanis during the winter months. It is essential to note that within this temperature range, the optimal temperature for growth and reproduction may vary as the fish undergoes different life stages.

- **Dissolved oxygen (DO)**

In Recirculating Aquaculture System (RAS), the preservation of water quality emerges as a critical factor influencing the well-being and survival of aquatic inhabitants. A persistent challenge in RAS management is the frequent occurrence of low dissolved oxygen (DO) conditions and elevated levels of fish waste metabolites in the culture water [85]. Dissolved oxygen, often expressed in parts per million (ppm) or milligrams per liter (mg/L), takes center stage as the paramount water quality parameter crucial for fish survival in such systems. To address these challenges, a continuous water treatment regimen is indispensable, serving the dual purpose of waste product removal from fish excretions and replenishing oxygen levels to ensure the optimal health and vitality of the aquatic population [56].

A study by Roncarati et al. [83] illuminates the pivotal role of water physicochemical parameters in RAS. Their investigation focused on the growth performance and survival of the common catfish, Ameiurus melas, within these systems. Notably, their findings revealed a significant advantage within the RAS environment, where the average DO level was recorded at 8.30 mg/L, starkly contrasting to the lower pond DO level of 7.28mg/L. This disparity in DO concentration highlights the considerable benefits of RAS in enhancing better fish production [83].

- **Total Suspended Solids (TSS)**

Managing effective waste solids control is a pivotal process in the operation of recirculating aquaculture systems [59]. The accumulation of waste solids in a RAS from feed fines, fish fecal matter, uneaten feed, algae, and biofilm cell mass sloughed from biofilters. These diverse particles are collectively referred to as Total Suspended Solids (TSS), varying in size from colloidal (0.001 to 100 μm dia.) to settleable solids (>100 μm dia.). Some TSS are large particles that can be filtered out of the water through mechanical filtration techniques, such as filter screens, sand filters, or swirl separators. Alternatively, they can settle out of the water column given sufficient "quiet" time. However, managing TSS within fish culture tanks poses unique challenges because conventional gravity-settling basins do not settle them out, and these solids are naturally resistant to settling due to their size and composition [86]. Consequently, successful

TSS removal necessitates the implementation of specialized treatment processes and the maintenance of high exchange flow rates within the system [87].

In practical terms, the removal efficiency of TSS highlights the variability between different aquaculture systems. During the experimental period, The TSS removal rate in the LRS (Low-Exchange Recirculating System) consistently exhibited a higher TSS removal rate compared to the Recirculating Aquaculture System [87]. Within the RAS, lower TSS removal values were recorded towards the end of the experiment, mirroring the influence of water exchange flow rates on TSS dynamics.

It is imperative to grasp that an increased TSS level can have detrimental effects on fish communities at multiple scales, from compromised spawning success and fry emergence at the individual level to broader ecosystem-level impacts, such as reduced species richness. This underscores the critical importance of robust waste solids control strategies in the operation of aquaculture systems [86,87].

- **Total Ammonium Nitrogen (TAN)**

Within intensive recirculating aquaculture systems, maintaining optimal water quality hinges on the meticulous control of Total Ammonia Nitrogen (TAN) [84]. Maintaining TAN levels below 1 ppm is imperative to ensure optimal conditions within these systems. TAN predominantly arises from fish excretion and manifests as a dual composition of ammonium ions (NH4+) and un-ionized ammonia (NH3). Crucially, NH3 poses a markedly higher toxicity risk to fish compared to NH4+; furthermore, the concentration of NH3 is intricately linked to environmental variables such as temperature and pH.

The relationship between pH and NH_3 concentration is particularly significant. As elucidated in David's study on European catfish, Silurus glanis, pond environments consistently exhibited higher TAN levels, often exceeding 0.3 mg/L, in contrast to recirculating aquaculture systems (RAS), where TAN levels typically remained around 0.2 mg/L. These findings align with the recommended TAN standard of 0 to 0.2 mg/L, underscoring the superior water quality concerning TAN levels in RAS. It is essential to recognize that even minor pH fluctuations, such as a one-unit increase from pH 7.0 to 8.0, can lead to an approximately tenfold increase in NH3 concentration in the water. In Summary, stringent TAN management, with a target of less than 1 ppm, constitutes a cornerstone of intensive recirculating systems.

Complementary System Components

TABLE 2: 8.5	**Status and performance overview of Common aquatic species reared in Recirculating Aquaculture systems (RAS)**					
	Species	**Country**	**Species Characteristics**	**Species Performance in RAS**	**Noteworthy Findings in RAS**	**Reference**
1	**Common Carp** *Cyprinus carpio*	Global distribution	Omnivorous Euryhaline Can tolerate a wide range of water temperatures and salinities.	Good growth performance High feed efficiency Tolerance to handling and intensive rearing conditions	Superior survival and growth performance in RAS compared to mudfish ponds.	Jelkic et al. [88]
					Improved survival and growth performance advantages of rearing grass carp (Ctenopharyngodon idella) juveniles in RAS.	Kristan et al. [89]
					An alternative perspective demonstrates that earthen ponds can yield better growth performance for Cyprinus carpio than RAS.	Mojer et al. [90]

2	**Tilapia** *Oreochromis niloticus*	Global distribution Native to Africa	Omnivorous Euryhaline Highly Adaptable Fast Growing	High growth potential Tolerance to high stocking density and water quality fluctuations Excellent feed utilization in RAS	Remarkable growth potential under varying RAS conditions, attaining marketable sizes quickly, contingent on specific system designs and initial weights.	Owatari et al. [91]
					Zero-discharge tilapia RAS with sedimentation basin, reducing nitrate and phosphorus concentrations for water reuse without compromising fish performance.	Shnel et al. [92]
					RAS mitigates the ecological impacts of tilapia rearing on the environment and biodiversity by minimizing discharge into the surrounding ecosystems.	
3	**Rainbow trout** *Oncorhynchus mykiss*	Globally farmed, Native to America	Carnivorous Coldwater Fish High Growth Rate Stress Tolerant	High stocking density Tolerant to cold water temperature. Good growth performance and feed utilization.	Embraced the intensive culture of trout in land-based RAS to adhere to environmental restrictions on effluent discharge.	Lasner et al., [93]
					Effluent treatment efforts for rainbow trout farms involved denitrifying bioreactors utilizing wood chips. They removed N-NO3 effluent from freshwater RAS, providing stable removal rates across temperatures from 4.5 to 15.6°C.	Von Ahnen et al.
4	**Atlantic salmon** *Salmo salar*	Globally farmed, Native to America	Anadromous Carnivorous Eurythermal Demersal Fast growing High-Ectoparasite Infestation-Lepeophtheirus salmonis	Have minimal negative impacts on water quality or environmental Impacts. RAS helps to control the spread of disease in the Salmon population. RAS can produce Salmonyear–round.	Challenges in sea cage farming due to high ectoparasite infestations have resulted in land-based RAS cultivation of Atlantic salmon, which is gaining momentum, particularly in Norway.	Davidson et al., Mota et al., [94,95]
					Land-based RAS cultivation in Norway aims to produce post-smolts weighing up to 1 kg.	Davidson et al., Good et al., [94]

5	***Pikeperch*** *Sander lucioperca*	Globally farmed, Native to the Eurasia	Voracious predator Euryhaline Benthopelagic Highly Territorial High growth rate and adaptability.	Suitable for RAS due to tolerance to cold water temperature. High feed Utilization	Research is ongoing in RAS to optimize pikeperch larvae and fry growth conditions, thus enhancing their survival and promoting growth in intensive-rearing environments.	Hermelink et al., [96]
6	**Striped catfish** *Pangasianodon hypophthalmus*	Globally farmed, Native to Southeast Asia	Omnivorous Euryhaline Benthopelagic Fast growing Highly Adaptable	Economic viability has proven favorable in intensive RAS production. Catfish has good growth performance and feed utilization in RAS.	A comparative study on striped catfish reared in RAS and traditional ponds yielded higher quantities of sludge, while RAS exhibited higher solid waste nutrient content and biogas yield. Vietnamese Pangasianodon spp. Cultured in RAS meet sustainability and stringent disease control certifications.	Nhut et al. [97]
7	**European catfish** *Silurus glanis*	Globally farmed, Native to Europe	Predatory Omnivorous Euryhaline Nocturnal Highly Territorial	Have minimal negative impacts on the environment and water quality. Controlled the spread of disease among the fish population.	The flesh quality of European catfish reared in RAS and outdoor farming units resulted in superior skinned trunk and fillet yields along with higher deposited fat weight.	Adamek et al. [12]
8	**European seabass** *Dicentrarchus labrax*	Globally farmed, Native to the Mediterranean and Atlantic oceans.	Marine Carnivorous Eurythermal Anadromous Highly migratory Fast growing	Intensively farmed in flow- through land-based systems and in sea cages.	Ongoing research in seabass RAS is progressing, with studies exploring the RAS potential for higher stocking densities.	Santos et al., [98]
9	**White leg shrimp** *Litopenaeus vannamei*	Globally farmed, Native to the Indo–Pacific region.	Omnivorous Euryhaline Benthopelagic High Disease tolerance Fast growing High Adaptability	Comparable production capacities for broodstock Shrimp in RAS. Significant growth and survival in co-culture with other aquatic species.	Comparable production capacities for broodstock shrimp in both RAS and flow-through earthen ponds.	Otoshi et al. [99]
					Co-culture of shrimp with red strain Nile tilapia has been proven to significantly enhance both species' survival and growth performance, leading to heightened economic benefits.	Sharawy et al., [100]
10	**Pacific oysters** *Crassostrea gigas*	Globally farmed, Native to Japan.	Filter feeders Euryhaline Benthic High Adaptability	Suitable for RAS due to their tolerance to varying water quality, including those with high temperatures and low oxygen levels.	The adoption of RAS holds great promise for the hatchery seed production of oysters, thereby supporting the growth of the aquaculture industry.	Mugwanya et al.

Table 1: Complementary System Components in Recirculating Aquaculture Systems (RAS).

Feed management in RAS

Feed is a critical component in Recirculating Aquaculture Systems (RAS), exerting significant influence over fish ingestion, growth, and metabolic processes [101]. Proper feed selection and feeding methods hold paramount importance for developing cultured organisms in RAS. Fish exhibit a high demand for protein but a lower efficiency in utilizing carbohydrates. Including an appropriate carbohydrate in their diet can enhance fish growth, feed conversion efficiency, and protein utilization [102].

Fish feed composition is a critical determinant of their nutritional intake. Protein, accounting for 65%-75% of fish dry matter, plays a multifaceted role in tissue and organ development and various physiological functions [103]. Fish require specific amino acids, including arginine, lysine, methionine, and phenylalanine, which must be supplied through their diet [5,104]. The majority of complete fish feeds include fish meal to provide these necessary amino acids and essential omega-3 fatty acids. Nonetheless, reducing the reliance on fish meal is essential for sustainable aquaculture, as excessive fishing pressure can be detrimental to the environment.

Traditionally, feed management relied on staff experience, but this method proved imprecise, resulting in uneven feeding and increased labor costs, which limited its application in large-scale industrial breeding [105]. Insufficient protein levels in feed can hinder fish growth. Furthermore, vitamins such as C and E are essential for fish immunity and feed preservation, while minerals like sulfur, phosphorus, calcium, sodium, potassium, and magnesium contribute to various bodily functions [104,106,107]. Additionally, including probiotics in RAS can enhance protein digestion, reduce bone deformities, accelerate fish growth, and alter bacterial composition [108].

Balancing feeding is crucial, as both underfeeding and overfeeding can lead to disease outbreaks and water pollution [109]. An excess of protein in feed can not only retard fish growth but also increase ammonia and urea discharge, negatively impacting the environment [103,110,111]. Proper feeding amounts are crucial to prevent an overload of feed load and the accumulation of contaminants in water [112]. Moreover, excess particulate matter can create a breeding ground for bacteria, thereby fostering disease [43].

Studies have indicated that feed's optimal protein and lipid ratios may vary depending on species and metabolic rates, with juvenile fish necessitating higher protein levels [5]. Feeding frequency and quantity are species-specific, with studies pinpointing optimal conditions for species such as Atlantic salmon [23] and red tilapia [113]. While increasing feeding frequency can somewhat enhance growth, there is a threshold beyond which no significant benefits are observed [101]. Nevertheless, the influence of feeding frequency may fluctuate depending on species and experimental parameters.

Precise feeding practices in RAS are essential for optimizing growth, reducing costs, and enhancing the overall sustainability of aquaculture. Diligent selection of feed ingredients, protein levels, and feeding strategies tailored to specific species are crucial considerations for successful aquaculture operations.

Diseases Control

The growing public demand for environment-friendly practices in the seafood industry and its expanding market have spurred the aquaculture sector to explore innovative and sustainable approaches. One such approach is the utilization of Closed Containment Recirculating Aquaculture Systems (RAS), designed to reduce disease outbreaks, minimize medication use, and ensure stable seafood production to meet market demands [59,114]. RAS technology offers numerous advantages, particularly in disease prevention and decreased reliance on medication. These measures encompass the use of disease-free eggs, enclosed facilities with limited access, a secure groundwater source, and strict employee adherence to biosecurity protocols. By doing so, RAS facilities can significantly reduce the risk of obligate fish pathogens gaining entry [59,114].

Fish are highly susceptible to stress from water quality and temperature fluctuations, leading to disease outbreaks and reduced farm productivity. In RAS farms with limited control over environmental conditions, such as those situated outdoors or in poorly insulated buildings, the system's instability can favor disease outbreaks due to variable temperature and ammonia removal rates. Ensuring stable environmental conditions is crucial to reduce stress-related susceptibility to diseases [115].

Before stocking fish, it is essential to confirm that the eggs are disease-free status to avoid significant losses. Some diseases, such as Infectious Pancreas Necrosis (IPN), Bacterial Kidney Disease (BKD), and certain herpes viruses, can persist even after disinfection. Once these disease organisms establish themselves in RAS, pathogens can be extremely challenging to eradicate, especially due to the sensitivity of nitrification bacterial colonies in the biofilters [116]. RAS systems may inadvertently promote the accumulation of opportunistic fish pathogens in the water column, biofilm, and fish due to prolonged water retention times, high fish densities, and continuous production techniques. As pathogen concentrations rise in RAS, the risk of disease outbreaks and losses intensifies. Unlike flow-through systems, traditional treatments for common trout diseases may not be practical in RAS settings due to the potential harm to nitrifying microbial populations [116].

Strict biosecurity practices are vital to prevent the introduction of fish pathogens from contaminated sources such as water supply, fish, feed, and eggs from suppliers. However, pathogens can still enter RAS farms via water vapor droplets, necessitating costly and time-consuming disinfection techniques [117]. Preventative measures include stress reduction, salt treatments, regular culling, and alternative therapies like low-dose peracetic acid and hydrogen peroxide when necessary. These treatments should consider their impact on biofilter performance and can help prevent widespread disease outbreaks.

The accumulation of nutrients and organic matter from uneaten feed and fish waste can create a favorable environment for various harmful microorganisms, including protozoa, bacteria, and fungi, which can negatively impact water quality and fish health [42,118-121]. Some parasitic diseases, including bacterial gill disease in freshwater systems, can be treated with ordinary salt. Formalin (HCHO) or hydrogen peroxide (H2O2) may be necessary for persistent parasitic organisms. Additionally, treatments like praziquantel and flubendazole solutions can effectively address ectoparasitic diseases. UV and ozone combined have shown promise in managing pathogens in marine RAS, while ozone and UV are effective in freshwater RAS [122].

Some experts advocate for rapid waste removal through ozonated protein skimming, while others prefer to mineralize waste within the RAS using anaerobic, submerged moving bed bioreactors to aid in denitrification. The latter approach can be beneficial, especially for reducing critical nitrate levels, which cannot be controlled solely through dilution in high biomass environments. However, adopting these approaches may vary due to additional investment costs and confidence in their application [123].

In conclusion, effective disease management and water quality control are critical for the successful operation of RAS in aquaculture, especially when aiming to meet the growing demand for sustainable seafood production [42,118-121,123].

Current Trends and Innovations in RAS

Although the fundamental principles of Recirculating Aquaculture Systems (RAS) appear advanced, there is a pressing need for significant technical advancements to enhance their performance across a wider range of culture conditions, animal species, and life stages. In conventional RAS, the primary water treatment methods rely on mechanical waste removal and biofiltration units, which have exhibited a relatively lower environmental impact, particularly in terms of mitigating eutrophication when compared to flow-through systems. The widespread implementation of automation, robotization, and cybernetic control systems in RAS operations remains a distant prospect, although their implementation holds the potential for groundbreaking innovations. Beyond the conventional engineering paradigm, it becomes increasingly evident that significant breakthroughs must arise from a deeper understanding of the intricate interactions between aquatic organisms and the RAS biotope. Such nuanced insights can potentially mitigate the ecological footprint of RAS technology further.

In recent years, RAS systems have witnessed successful integration of sludge denitrification reactors [124]. These upflow sludge reactors operate under anoxic conditions and are fed with dissolved and particulate fecal organic waste, serving as a substrate for denitrifying bacteria within the sludge bed. The reactor's design ensures that organic waste and bacterial flocs enter from the bottom, with the upflow velocity intentionally maintained below the settling velocity to create a sludge bed at the reactor's base. Managing sludge discharge from RAS systems entails various logistical challenges, including the need for various storage facilities, transportation, labor, and disposal fees, as emphasized by Schneider et al. [125]. Various thickening technologies have been proposed to address these challenges, such as belt filter systems [126] and geotextile bags or tubes [122,127]. Incorporating geotextile bag filters in RAS is an effective pretreatment method, particularly when dealing with dewatering total suspended solids (TSS) before disposal [127]. This approach is advantageous because it allows for the leaching of dissolved organic carbon and Chemical Oxygen Demand (COD) from the waste, supporting denitrification or leaching of inorganic nitrogen and phosphate (PO4) from the waste to provide essential nutrients for downstream hydroponic operations or field crops [126]. Using geotextile bags results in a notable 10% conversion of solid waste into dry matter after just one week of dewatering. While this method may entail higher costs than conventional RAS practices, it offers the distinct advantage of substantially reducing phosphorus (P) levels within aquaculture effluents, thereby promoting sustainable aquaculture production [128].

Recent developments in Recirculating Aquaculture Systems (RAS) have brought forth noteworthy innovations [27]. These advancements encompass sludge thickening technologies, denitrification reactors, ultraviolet and ozone irradiation treatments, and enhancements in fish production. Collectively, these innovations have yielded substantial benefits, notably in terms of reduced water consumption, waste discharge, and energy utilization within

RAS operations. The discharged water from RAS systems can now be efficiently repurposed, either as valuable fertilizer or as an integral part of an integrated complex, further enhancing the overall sustainability of RAS technology [27].

Applying ozonation and UV treatment in Recirculating Aquaculture Systems (RAS) has emerged as a promising strategy for enhancing filtration and reducing organic matter accumulation [122]. Ozone has found diverse applications in RAS, including pathogen control, oxidation of NO_2 to NO_3, breakdown of organic matter, Total Ammonia Nitrogen (TAN) treatment, and the removal of fine suspended particles. The efficacy of ozone in these aspects has been demonstrated by studies conducted by Summerfelt et al. [122], Tango and Gagnon [129] and Bullock et al. [130].

Moreover, the integration of ozonation has shown significant improvements in microscreen filter performance, concurrently mitigating the accumulation of dissolved matter that can adversely affect water color [122]. The literature extensively documents the efficacy of combining ozone with UV treatment to control both heterotrophic and coliform bacteria effectively counts in freshwater RAS [117].

However, it is crucial to acknowledge that the application of ozone in marine RASs may lead to elevated bromate concentrations that could potentially impact fish health [129]. Therefore, further investigation is needed to elucidate the potential consequences of ozone application within RAS systems on fish health.

In recent years, integrating algal ponds and wetlands as water treatment units alongside Recirculating Aquaculture Systems (RAS) has garnered considerable attention due to its potential to manage aquaculture effluents effectively. Effluents from fish tanks, ponds, or raceways are notably more diluted, typically 20–25 times more than the medium-strength municipal wastewater commonly treated in constructed wetlands [130].

Constructed wetlands leverage wetland vegetation, soils, and associated microbial communities to treat and concentrate wastewater effectively [131]. A comprehensive review of two decades of constructed wetland operation in Denmark, conducted by Brix et al. [132], concluded that these systems reduce Biological Oxygen Demand (BOD) and organic matter. However, their removal efficiency for nitrogen (N) and phosphorus (P) typically ranged from 30% to 50%, with minimal nitrification occurring in these horizontal subsurface flow systems. Incorporating partial recirculation in vertical flow-constructed wetlands has enhanced nitrogen removal through denitrification [133]. This strategy stabilizes system performance and enhances nitrogen removal via denitrification [133]. Furthermore, significant removal rates were achieved when combining sub-surface constructed wetlands with screen filtration, and this integrated approach achieved a removal efficiency of 92% for NO_2, 81% for NO_3, and 64% for particulate matter [134].

Plant species within wetlands play a crucial role in removing organic matter and N_2, while sediments aid in removing P [135]. Additionally, microalgae have been employed in wastewater treatment, aiding in removing Chemical Oxygen Demand (COD), BOD, nutrients, heavy metals, and pathogens. Furthermore, anaerobic digestion of algal-bacterial biomass can yield biogas [136].

High-rate algal Ponds (HRAPs) have been strategically designed to synchronize algae production and oxygen (O_2) generation with the Biochemical Oxygen Demand (BOD) of the influent [137]. HRAPs, being low-energy wastewater treatment plants, have achieved impressive BOD removal rates of up to 175 g/m^3/day, a significant improvement compared to traditional waste stabilization ponds, which typically achieve only 5–10 g BOD removal [138]. A modified version of HRAPs has been adapted for wastewater treatment in Partitioned Aquaculture Systems (PAS). In France, HRAPs have been integrated with RAS for sea bass, serving as a secondary wastewater treatment method to reduce nutrient discharge from the system [139,140].

A commercial integrated shrimp–algae–oyster culture system in Hawaii that reduces water consumption and transforms effluent treatment into a profitable endeavor [141]. This example highlights the economic potential of sustainable wastewater management in aquaculture.

Challenges and Future Prospects in RAS

The challenges and potential of Recirculating Aquaculture Systems (RAS) make it a sustainable technology with significant implications for the growth of the aquaculture industry. RAS is widely recognized as one of the most promising and efficient methods for fish production, offering numerous benefits. Additionally, RAS has demonstrated its effectiveness in safeguarding cultured species against disease outbreaks within aquaculture farms. However, the capital-intensive nature of RAS operations necessitates substantial funding for various aspects, including infrastructure, equipment, effluent and influent treatment systems, construction, engineering, and management. The continuous circulation of the same water system within the system presents a unique challenge regarding disease prevention and treatment.

The commendable progress achieved with Moving Bed Biofilm Reactors (MBBRs) as biofilters in the aquaculture industry, particularly in RAS wastewater treatment. Nevertheless, it is crucial to recognize that the microbial community structure in MBBRs can be significantly affected by varying salinities, impacting the performance of the nitrification process in wastewater treatment. Therefore, there's a growing imperative for research to improve the efficiency of processes and materials through innovative measures in the future. Moreover, some researchers are exploring converting solid waste into fish feed. Pathogens can spread throughout the RAS system, and introducing chemicals and antibiotics may disrupt the microbiome of the biofilters, leading to potential biofilter failure and varying levels of toxic ammonia or nitrite in the water, which can harm aquatic animals [142].

Another major challenge involves identifying cost-effective and suitable halophilic microorganisms for nitrifying bioreactors for mariculture effluent treatment. Although MBBR biofilters have gained popularity, research focused on nutrient and organic matter removal in MBBRs lags behind studies on activated sludge and other conventional reactors. The design of MBBR systems is influenced significantly by the biofilm carrier, emphasizing the need to develop and apply more sustainable, environmentally friendly carriers with significant potential in wastewater treatment [143,144].

Low-water exchange RAS systems are more susceptible to infections in aquatic animals compared to high-water exchange systems like flow-through tanks [77]. While RAS offers numerous advantages, it also introduces potential risks related to latent diseases and public health concerns. The recycling of water in RAS systems can result in the incorporation of pathogens into the biofilm, resulting in repeated exposure of fish to pathogens and the presence of asymptomatic carriers.

The study of Solids Nitrogen Denitrification (SND) and other nitrate removal processes in RAS wastewater presents promising results due to their efficiency in terms of energy consumption, operation time, and space requirements. However, further research is essential to comprehensively understand SND mechanisms and optimize their application in both freshwater and saline aquaculture water within MBBR systems.

Developing innovative strategies for SND processes that minimize or eliminate the need for additional external carbon sources is desirable, addressing the economic requirements of the aquaculture industry. Various innovative approaches, such as SID bioreactors, Müller-belecke et al. [145], SNAD bioreactors [143,146,147] and hybrid MBBR systems all of which require further investigation and development.

The current state of Recirculating Aquaculture Systems (RAS) research needs several key future perspectives to enhance their efficiency and ecological sustainability. The primary areas of focus include:

Improving Water Resource Utilization

The future perspective of RAS research emphasizes the need to improve the utilization of water resources. Automation and digital technologies are paramount in advancing aquaculture environmental control, making recirculating equipment smarter, and optimizing resource utilization efficiency. This approach aims to reduce production costs and ultimately achieve precision farming.

Elevating Waste Removal Efficiency

A significant research priority is improving RAS's ecological sustainability by enhancing waste removal efficiency, specifically targeting solids, nitrogen, and phosphate. Current RAS systems excel in managing nitrogenous wastes but face challenges in managing solid wastes. Research efforts should develop innovative technology and equipment to remove suspended particulate matter effectively. Additionally, existing removal technologies like biological flocculation, membrane filtration, ultrasonic treatment, and tank design should undergo refinement for better removal efficiency.

CO_2 Removal and Green Energy

RAS research should increase its focus on CO2 removal equipment and temperature control to achieve zero-emission standards. This includes developing and comprehensively utilizing green energy sources like geothermal energy, solar power, and water energy. Additionally, improving the efficiency of aeration equipment, particularly in pure O2 utilization, emerges as a pivotal facet in preventing wastage.

Optimizing Feed Efficiency

Feed efficiency is another crucial area for future research in RAS. As the landscape of resources evolves, it remains crucial to consider digestibility and using feed ingredients when crafting specific RAS diets. Furthermore, supplementing feeds with high-viscosity guar gum can improve fecal stability and mechanical treatment efficiency [148,149].

Automation and Large-Scale Implementation

Future RAS research should prioritize automation, safety, and environmental protection, developing new integrated systems, such as wetlands and algal-controlled systems [27] and aquaponics, [150,151]. Implementing automation and human-friendly operation modes can significantly promote large-scale adoption and cost savings.

Refining Faecal Characteristics

Future research should optimize fecal matter characteristics in RAS. The overarching goal is to generate fecal matter that can be easily removed from the water, generate fewer fine solids, and support efficient fermentation by the microbial community within the system. Studies have demonstrated that diet composition, starch inclusion, and gelatinization can influence fecal removal rates [149].

Addressing Fine Solids Challenges

A notable bottleneck in RAS is the ineffective removal of fine solids from the water [69,152]. Research should encompass innovative tank designs, enhancements to solids removal systems, and hydraulic conditions to tackle this problem effectively. Application of ozone in marine RAS for water quality improvement may influence fine solids characteristics, necessitating further investigation [129,153,154].

In summary, the future of RAS research lies in optimizing water resource utilization, improving waste removal efficiency, enhancing feed efficiency, embracing green energy alternatives, refining fecal characteristics, embracing automation and large-scale implementation, improving nitrogen and CO2 removal, and effectively tackling the challenges associated with fine solids and suspended solids management. These research directions aim to make RAS more efficient, environmentally friendly, and economically sustainable for advancing aquaculture Practices.

Conclusion

In pursuing sustainable food production to meet the demands of a growing global population, the concept of "sustainable intensification," as articulated by Godfray et al. [155-180], becomes paramount. This paradigm emphasizes the necessity of enhancing food output from existing land while minimizing environmental impacts. Amidst the diverse array of aquaculture production systems currently in operation, Recirculating Aquaculture Systems (RAS) promise to achieve high production yields while preserving optimal environmental conditions and ensuring animal welfare, all while exerting minimal ecological pressures.

The continuous evolution of RAS systems is pivotal, but this evolution is contingent upon effective communication within the industry for the future of sustainable aquaculture. This entails active stakeholder engagement, including producers, suppliers, researchers, and consultants. In today's interconnected world, social networks serve as invaluable platforms, serving as the bridge that unites the community engaged in RAS research and practice [180-198].

Despite the manifold advantages of RAS, its widespread adoption has faced hurdles, including a scarcity of expertise, substantial initial investments, and the elevated operational costs associated with biofilters. Currently, RAS adoption is witnessing growth in Europe, encompassing grow-out operations for freshwater species like eel and catfish alongside marine species like turbot, seabass, and sole. Developed countries predominantly employ these systems for nursery rearing and broodstock management.

Yet, even as recent strides have fortified the environmental sustainability of RAS, a potential concern arises from the accumulation of substances in the water due to reduced water exchange rates. Ongoing research endeavors are dedicated to mitigating operational costs and identifying species well-suited for RAS cultivation. Furthermore, the evolution of water treatment technologies, including sludge thickening techniques, denitrification reactors, and ozone applications, has enabled the reduction of water exchange rates, paving the way for nearly closed systems that yield valuable waste products that find utility in Integrated Multi-Trophic Aquaculture (IMTA) or Integrated Aquaculture Agriculture (IAA) systems.

Navigating the evolving landscape of RAS necessitates a deeper understanding of the intricate interactions between fish and the system. While technical and engineering knowledge plays a pivotal role, the successful management of RAS requires practical experience. In essence, gaining an interplay among its constituent elements is indispensable to address future challenges effectively.

In summation, RAS represents a promising avenue for sustainable aquaculture, aligning seamlessly with the principles of sustainable intensification. The path forward requires ongoing research, a collaborative approach, and an unwavering dedication to fathom and harness RAS's full potential in meeting ever-evolving global food production demands.

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