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Recirculating Aquaculture Systems (RAS): A Sustainable and Technology-Driven Future for Aquaculture

Vishal K. Solanki[1], Nilesh H. Joshi[2]; Anjali R. Baraiya[3]
[1] Senior Research Fellow, (Ph. D.) Aquaculture, Centre of Excellence in Seaweed Research and Utilization, Kamdhenu University, Okha, Gujarat, India
[2] Associate Professor & Head, Centre of Excellence in Seaweed Research and Utilization, Kamdhenu University, Okha, Gujarat, India
[3] M. F. Sc. Department of Fishe Processing Technology, College of Fisheries Science, Kamdhenu University, Veraval, Gujrat, India
Corresponding author's email: *vishalsolankiabc@gmail.com*
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1. Introduction: Why Aquaculture Needs a Smarter System

What would happen when fish could be grown with 5-10% of the amount of water needed in the traditional ponds? It is not a futuristic idea but the basic promise of smarter and more sustainable feeding our planet (Ahmed and Turchini, 2021). Global aquaculture production is the fastest-growing food production sector in the world, with its output growth more than 600 per cent since 1990. As the world population is predicted to be 9.7 billion by 2050, the demand of seafood protein is set to almost increase twofold (Brown et al., 2025). Since capture fisheries are almost stagnant, aquaculture is the only solution to the growing disparity between seafood demand and supply rates (Ahmed & Turchini, 2021).

Nevertheless, the traditional fish-farming methods are nearing a critical point of departure. The problem of freshwater shortage has become one of the world-wide crises, compelling aquaculture to compete directly with other urban water uses and agricultural irrigation over scarce water resources (Ahmed and Turchini, 2021). The pond-based systems are traditionally very water-consumptive; in certain occasions, one kilogram of fish can be produced by losing up to 35 cubic metres of water to seepage and evaporation (Ahmed & Turchini, 2021). Besides the consumption of water, the systems also require large land areas which most of the time invade ecologically sensitive areas. The past practices of coastal aquaculture have a history of habitat degradation, such as the extensive destruction of mangrove forests, and of large areas of valuable land (Ahmed and Turchini, 2021; Ropicki et al., 2024).

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Similarly worrying are the environmental effects of the conventional traditional open aquaculture systems like sea cages. These systems normally discharge untreated feed, faces and metabolic waste into the immediate waters resulting in the enrichment of nutrients, water pollution and eutrophication (Ahmed and Turchini, 2021; Brown et al., 2025). Besides, open systems are very sensitive to environmental change and disease pressures, often having outbursts of pathogens and parasites including sea lice that may infect wild fish stocks, disrupt local ecosystems (Ahmed and Turchini, 2021; Brown et al., 2025).

To get out of this unstable linear model of production take-do-discard, another production system called Recirculating Aquaculture System (RAS) has become an engaging alternative (Zimmermann et al., 2023). RAS is an indoor farming technology that is ground-based and in which fish are farmed under complete control (Ahmed and Turchini, 2021). RAS can process a maximum of 99 percent of its water daily by combining a complicated mechanical filtration procedure and biological treatment to purify and reuse it (Van, 2013; Brown et al., 2025). These systems need less than 1 percent of the area of conventional aquaculture, help to protect stocks against natural disasters, and offer a highly bio secure environment that greatly diminishes the risk of diseases and the use of antibiotics (Ahmed and Turchini, 2021; Li et al., 2024). Consequently, the idea of RAS is a super-intensive but eco-friendly way to achieve the sustainability of seafood production in the resource-depleting world (Ahmed and Turchini, 2021).

2. What is Recirculatory Aquaculture System (RAS)?

Recirculating Aquaculture System (RAS) is a new form of land-based fish-rearing facility that has little contact with the environment around it (Van, 2013). Simply put, it is a high-density model of aquaculture, which is based on successive treatment procedures to clean water continuously to result in reuse (Li et al., 2024). In contrast to conventional farming methods, RAS, like a closed or semi-closed production cycle, uses water about 90 to 99 percent daily; it recycles the water (Lindholm-Lehto, 2023; Zimmermann et al., 2023).

The system works based on the continuous treatment cycle that has been established to ensure that the aquatic environment remains at a constant and high-quality state to support the growth of fish. Water is pumped into a specified flow: through a fish tank to a mechanical filter, which removes solid wastes (faeces and uneaten feed), then to a biofilter, which takes advantageous microorganisms that transform toxic ammonia into less harmful nitrate, and finally to a point of oxygenation, which replenishes dissolved oxygen into the water, which is returned to the fish tank (Xiao et al., 2019; Gupta et al., 2024).

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The conventional pond culture requires huge land space and natural water supply and tends to be prone to environmental variations, predators and epidemics. Such systems are characterized by low stocking levels and provide a low level of control over water quality (Li et al., 2024; Zimmermann et al., 2023).

Flow-through systems ensure that the water only flows in and out of the culture tanks then it is discharged into the environment. Although they are more controlled than ponds, these ponds need constant and substantial supply of water and that it may consume up to 50 cubic metres of water to produce one kilogram of fish (Martins et al., 2010).

RAS are considered as being of a "super-intensive type. Through water treatment and reuse in the system, RAS can cut down land demand by over 99 percent and significantly decrease water usage in contrast to conventional approaches (Li et al., 2024).

Due to RAS offering year-long, constant production environments that are not affected by seasonal and climatic changes, it is being adopted to grow a variety of commercially viable species (Ahmed & Turchini, 2021). Some of the most cultured freshwater species are tilapia and African catfish because they are resilient and can withstand high stocking; therefore, they are tolerant to high stocking levels (Li et al., 2024; Zimmermann et al., 2023). Shrimp especially the Pacific white shrimp has become a popular RAS candidate in marine and brackish-water systems (Li et al., 2024). At the global scale, one of the brightest examples of RAS success is Atlantic salmon, where commercial facilities on large scale are held in Norway, Canada and the United States, to create fish nearer to the primary consumer base (Brown et al., 2025; Ropicki et al., 2024).

3. Large-scale elements of a Recirculating aquaculture System (RAS)

A Recirculating Aquaculture System (RAS) is an interdisciplinary agricultural technology based on biological, mechanical, and information technology to establish a highly controlled and a stable aquaculture space (indoor) (Li et al., 2024; Xiao et al., 2019). In contrast to the conventional pond systems which are exposed to the natural environment changes, RAS is based on the set of highly specialized components that are used to treat, monitor, and reuse the water to produce intensive fish with minimal resource consumption (Xiao et al., 2019).

Fish culture tanks are in the centre of the system, and their design and construction have a direct impact on the fish health, the efficiency of the water circulation, and the effectiveness of the waste removal (Xiao et al., 2019; Grandez-Yoplac et al., 2025). Concrete, fibre-reinforced plastic (FRP), and high-density polyethylene (HDPE) are some of the common materials used in modern RAS facilities due to their durability and the lack of toxicity

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(Brown et al., 2025). The use of circular tanks is usually favoured because they produce rotating water circulation which gathers the solid wastes at the centre facilitating easy clearing by means of central drains. Specific species that need directional flow are also addressed in rectangular raceways (Grandez-Yoplac et al., 2025). Higher filtration and oxygenation allow RAS tanks to accommodate super-intensive stocking levels, which may be as high as 130 kg of fish per cubic metre (Li et al., 2024).

The initial process of water treatment in RAS is mechanical filtration that helps take care of solid wastes like uneaten feed and fish faeces before they decompose and raise water quality standards (Xiao et al., 2019; Gupta et al., 2024). It is vital to be fast in removing suspended solids since these particles may harm the gills of fish, block biological filters and use dissolved oxygen. The most common types of mechanical filtration units are drum filters with fine microscreens, settling tanks where the heavier particles are removed with the help of gravity, and screen filters where the separation of the solids is achieved with the help of mesh particles (Van, 2013; Xiao et al., 2019).

Biological filtration is also considered the centre of RAS since it eliminates dissolved metabolic wastes that mechanical filters are unable to trap (Martins et al., 2010). Nitrifying bacteria forms grow as biofilms on specifically designed surface and transform toxic ammonia released by fish into nitrite and subsequently into less toxic nitrate, the process called nitrification (Lindholm-Lehto, 2023). Other biofilter designs that have been the most prevalent in RAS include the Moving Bed Biofilm Reactors and trickling filters (Gupta et al., 2024).

Aeration and oxygenation systems are used to sustain high levels of dissolved oxygen, disinfection and monitoring systems, including UV sterilization and sensor-based water quality control are applied to ensure biosecurity and stable environmental conditions to support intensive production (Xiao et al., 2019; Grandez-Yoplac et al., 2025).

4. The merits of RAS Technology.

Recirculating Aquaculture Systems (RAS) is a significant change in the modern aquaculture as it provides an efficient, sustainable, and highly controlled approach to seafood production. With the global demand of fish ever-increasing and the natural resources becoming increasingly scarce, RAS offers solutions to most of the environmental, production, and biosecurity challenges that the conventional aquaculture systems face.

Environmental Benefits

The great water-use efficiency of RAS technology is considered one of the greatest advantages. Daily, these systems can recycle 90-99 percent of the total amount of water, which makes them especially useful in the regions with a shortage of freshwater (Ahmed and Turchini, 2021; Van, 2013). Due to the nature of RAS being a closed or semi closed system waste is not released into the surrounding ecology. Rather, solid wastes undergo concentration into sludge which can be treated safely or even used as farm fertilizer (Martins et al., 2010). This will reduce; by a large margin, pollution, organic loading, and eutrophication of natural water bodies, which have been mostly linked to open-water cages and flow-through systems (Gupta et al., 2024; Brown et al., 2025).

Production Benefits

RAS technology facilitates the culture of fish on a super-intensive level, where the stocking density may be as high as 130 kg of fish per cubic metre. It enables the use of productivity orders of magnitude higher than with traditional pond systems (Xiao et al., 2019; Ropicki et al., 2024). Due to the accurately controlled temperature, oxygen levels, and parameters of water quality, fish are less stressed, healthier, and develop at a faster rate. It also improves the feed conversion efficiency, reducing the cost of production, and reducing the waste of nutrients (Li et al., 2024; Brown et al., 2025). Moreover, RAS allows one to produce the product throughout the year regardless of the seasonal fluctuations, providing the market with the predictable and constant number of fish (Zimmermann et al., 2023).

Biosecurity Benefits

The biosecurity level is high because of physical division between the RAS facilities and the natural water bodies. Wild pathogen and parasite and predator attacks on the fish stocks are eliminated, and the chances of epidemics are lowered to a considerable degree (Ropicki et al., 2024). This consequently leads to a decrease in the use of antibiotics and chemical treatments. Most prevention measures are typically implemented in the form of vaccination, high-hygiene standards, and a healthy management of advantageous microbial communities, which make seafood safer to consumers and have a reduced environmental cost (Rurangwa et al., 2015; Gupta et al., 2024).

Benefits of land and Urban Use.

RAS is highly land-efficient, consuming under 1 percent of the land utilized in the traditional extensive aquaculture (Li et al., 2024). Its small size enables the facilities to be set up near urban centres, minimising the cost of transportation and carbon emissions and bringing fresher fish to consumers (Brown et al., 2025). Besides, since RAS does not require fertile soil or natural water bodies, it is quite appropriate in desert, coastal, and even arid areas (Van, 2013).

5. Problems and drawbacks of RAS.

Although the Recirculating Aquaculture System (RAS) technology has very significant benefits, a few challenges have been associated with it that could restrict its application, especially in developing countries. The first factor that is the biggest limitation is the high startup capital cost. To create a contemporary RAS plant, a lot of money will have to be spent on infrastructure, including special culture tanks, mechanical and biological filtration units, oxygenation systems, and real-time monitoring devices. They are much more capital-intensive when compared to the traditional pond or cage-based aquaculture, which makes it hard to enter small-scale farmers (Gupta et al., 2024; Zimmermann et al., 2023).

Besides high set up costs, the operations of RAS require qualified and technologically scientific human resources. To manage the system effectively, it is necessary to have a proper knowledge about fish biology, microbiology, water chemistry and mechanical engineering. Any minor malfunctions in the work process, including overfeeding, poor care of biofilter, and slow reaction to changes in water quality, may interfere with the useful bacterial community and destabilize the system (Ropicki et al., 2024). This technicality predisposes operational risk especially in areas where there are a few trained people.

This is also one of the key weaknesses because the system will require uninterrupted energy. Fish have high oxygen consumption because the facilities at RAS stock at super-intensive densities. Power outage particularly due to back-up failure can cause serious shortages of oxygen and mass death in a few minutes (Badiola et al., 2018). This means that, good electricity and backup power systems are a must, which increases costs of operation and requirements of infrastructure. The water quality management is another technical challenge that is still in process. The operators should be very keen on the control of the toxic nitrogenous wastes that include ammonia and nitrite, and the level of carbon dioxide. Moreover, off-flavour compounds such as geosmin and 2-methylisoborneol (MIB) may lead to unfavourable fish taste and must be further managed prior to harvest (Lindholm-Lehto, 2023; Azaria and Van Rijn, 2018).

However, the future of RAS is bright. As the scale of operation increases, the operational experience and advancement in technology, the cost of production is likely to reduce. RAS has been accepted as a strategic approach to food security and environmental sustainability by many governments, and incentives and training are now given to encourage its use (Li et al., 2024). With the increase in expertise and the efficiency of systems, most of the existing constraints of RAS should be reduced.

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6. RAS in India: Current position and prospective.

India is gradually becoming a key player in the world Blue Revolution and Recirculating Aquaculture Systems (RAS) is being referred to as a solution to the production of seafood in the future. The growing stresses on land, freshwater, and coastal ecosystems have increased the appeal of land-based, intensive aquaculture systems throughout the Asia-Pacific area, and India is slowly joining in (Li et al., 2024; Gupta et al., 2024).

Current situation in RAS in India.

Currently, RAS use in India is at an early stage and indicates encouraging sub variation in use. It has been used most successfully and firstly in the culture of ornamental and high-price marine fish. Experimental breeding, rearing and seed production of species, including Pseudanthias marcia (*marcia anthias*) and *Lethrinus lentjan* (red spotted emperor), has been established as successful in controlled RAS conditions through research trials.

The other sector is tilapia cultivation especially by use of Partitioned Aquaculture Systems (PAS) like the In-Pond Raceway System (IPRS). These systems are RAS based systems with pond culture that enable the production to be high-density, the water quality can be improved and eliminated or reduced effluent can be discharged. Secondly, RAS has been applied to shrimp nurseries and hatcheries in large scale since despite the absence of large-scale shrimp grow-out RAS in India, the technology has demonstrated high biosecurity and pathogen control, such as Vibrio.

Future Prospect and Future Openings.

RAS has a large potential in the future in India. The government policies, enabling legislation and economic incentives are also becoming increasingly recognized as the major force behind growth. Cost reduction, automation and integration of IoT-based monitoring systems are actively being research and university institutions and emerging startups. RAS promises significant possibilities to urban aquaculture, through the possibility of local production and local consumption of product, close to urban markets, with the aim of minimizing transportation expenses and carbon emissions. RAS is also a climate resistant technology that offers defence against cyclones, extreme temperatures and changes in salinity. As the demand on high-quality and traceable seafood rises, India has a good chance to create export-based RAS production and be a force to reckon with in the international market of aquaculture.

7. Conclusion: RAS the Future of the Aquaculture?

Since the world is expected to have about 9.7billion inhabitants in the year 2050, the means of having a sustainable supply of quality protein has been identified among the most

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challenging issues of our time. Aquaculture will be the key to this demand, and Recirculating Aquaculture Systems (RAS) can be considered one of the most promising solutions. Recycling water (up to 99 percent) and reusing waste (to form the manageable sludge) will lead to a significant drop in pressure on freshwater resources, at the same time avoiding environmental pollution and habitat degradation.

Besides environmental sustainability, RAS is also a technological advancement of the aquaculture industry. Automation, real-time sensors, IoT, and artificial intelligence allow one to control the quality of water accurately, fish health, and feeding efficiency. This leads to quicker growth, better biosecurity, production all-year round, and quality of products. Even though current high capital investment, energy dependence and high skilled manpower requirements make rapid adoption difficult these factors will reduce with emerging technology and economies of scale is realized.

RAS can revolutionize the aquaculture industry by making it climate resilient, urban-friendly and environmentally responsible food production system through the adoption of supportive government policies, specific training programmes, and ongoing innovation. Finally, RAS is not only an alternative system it is a necessary stepway to addressing the future generation of seafood demand without depleting the natural resources of the planet.

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