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# Recirculatory Aquaculture Systems: Sustainable Fish Farming

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### Abstract

Recirculatory Aquaculture Systems (RAS) are tank-based production systems that clean, treat and re-use water within a closed or semi-closed loop; they offer an intensive, space-efficient alternative to ponds and flow-through systems. By retaining water and nutrients on-site and applying engineered waste-treatment processes (mechanical removal, bio-filtration, disinfection and solids management), RAS can sharply reduce freshwater withdrawals, improve biosecurity and enable controlled production of high-value species near markets. Those advantages come with trade-offs: higher capital intensity, significant electrical energy demand and a learning curve in operation and monitoring. This article synthesizes the technology, biological and engineering foundations, operational best-practices, environmental and economic trade-offs and practical pathways for farmers and policy makers who want RAS that are both productive and genuinely sustainable. It emphasizes pragmatic design choices matching species and stocking density to treatment capacity, prioritizing energy and heat recovery and building redundancy into life-support systems so that RAS becomes not just an engineering showcase but a resilient food-production tool that fits local goals and constraints.

**Keywords:** Recirculating Aquaculture Systems, RAS, bio-filter, solids removal, energy efficiency, water reuse, biosecurity, life-support systems, aquaculture economics, sustainable fish farming

### Introduction

As global demand for seafood grows and pressures on wild stocks and freshwater resources mount, tank-based systems that recycle water are attracting attention for their potential to deliver reliable supplies of fish with a smaller water footprint and better site flexibility. RAS are not a single recipe: they span small hatchery systems and multi-hectare

industrial facilities, freshwater and marine species and hybrid designs that combine flow through and partial recirculation. What unites them is the same engineering challenge maintain water quality and biological stability while minimizing waste and energy cost so fish can grow fast and healthily in dense, managed environments. Early adopters have demonstrated clear gains in biosecurity and proximity-to-market logistics, while research and commercial reports are steadily improving the design and operational playbook for energy and cost optimization.

### **Core components and biological foundations**

A functioning RAS is a marriage of biology and engineering. At the simplest level the loop contains culture tanks, solids-removal modules, biological filters, oxygenation systems, temperature control, disinfection and monitoring & control hardware. The biological heart of many systems is the nitrifying bio-filter: a matrix or fixed-media bed where autotrophic bacteria convert toxic ammonia (excreted by fish) to nitrite and then to nitrate. Stable bio-filter performance is critical because ammonia and nitrite spikes are among the most common causes of acute mortality in intensive systems. In practice, operators balance ammonia production (driven by feed and biomass) with bio-filter capacity, organic solids removal and water-exchange strategies to maintain safe concentrations.

### **Solids, organics and nitrogen management**

Solids from uneaten feed, faeces and bio floc are the invisible workload in a RAS. If left suspended, fine particulates fuel heterotrophic bacterial blooms that consume oxygen and destabilize bio-filters. Good systems therefore use multi-stage solids management: coarse settling or swirl separators, mechanical drum or sand filters for smaller particulates and sometimes micro screens or foam fractionators for very fine organics. Part of the nitrogen story is managing dissolved nitrogen species: nitrification produces nitrate, which is less toxic but accumulates; many commercial RAS accept a controlled nitrate level and remove it by periodic dilution or by adding denitrification stages (anoxic reactors) or plant/microalgae polishing in integrated approaches. The practical takeaway is that solids control and nitrogen control are tightly coupled; neglect one and the other becomes harder to manage. (No single filter solves every problem; right-sizing and staged treatment are keys.)

### **Oxygen, temperature and dissolved-gas control**

Water quality is not just chemistry it's physics. Dissolved oxygen must stay within species-specific safe ranges, which becomes technically demanding at high stocking densities. Aeration (compressors and diffusers) is common, but oxygen injection (liquid oxygen) is often more efficient where demand is high. Degassing units remove excess CO<sub>2</sub> and nitrogen super saturation (which causes gas bubble disease). Temperature control via heat exchangers, geothermal, or waste-heat recovery has a strong influence on growth rates and feed conversion;

when thoughtfully integrated, heat-recovery systems can flip energy balances by using fish-metabolism heat to warm incoming water rather than burning fuel. Good control strategies combine sensor-driven feedback loops with operational simplicity: stable water temperatures, stable oxygenation and conservative safety margins are what spare you the most sleepless nights.

### **Energy and greenhouse-gas considerations**

Energy is arguably the Achilles' heel of many RAS designs: continuous pumping, filtration, oxygenation and heating can translate to several kWh per kilogram of fish produced estimates in the literature vary with species, climate and system choices. That said, design decisions (vertical vs horizontal tank layouts, high-efficiency pumps, gravity-assisted flows, optimized oxygen delivery, heat recovery and partial integration with on-site renewable energy) substantially reduce energy intensity. Life-cycle assessments that include feed sourcing, transport and land-use changes show that RAS can be competitive or even advantageous in greenhouse-gas terms in some geographies, particularly when systems reduce long-distance transport or displace emissions-intensive feed or processing steps; however, the energy story must be expressly part of feasibility studies, not an afterthought.

### **Species, stocking density and biological performance**

RAS excel with species that command higher market prices, have predictable feed behaviour and tolerate intensive rearing: salmonids (at various life stages), trout, turbot, barramundi and tilapia are commonly farmed in tank systems; shellfish and shrimp have seen experimental and commercial RAS adaptations as well. Freshwater warm water species generally require less technical water chemistry control than marine species, but market value drives choices as much as biology. Stocking density is a system-specific parameter: rather than maximizing kg/m<sup>3</sup>, sustainable practice optimizes growth rate, feed-conversion ratio and animal welfare higher densities increase throughput but also magnify the consequences of a treatment failure. Pilot studies and gradual scale-up from fingerling to commercial density are best practices.

### **Economics, business models and risk management**

Capital expenditure for RAS tanks, filters, sensors and building infrastructure tends to be higher than for ponds or raceways per unit of installed production capacity. Operational costs are also different: fewer labour hours per hectare can be offset by higher feed, energy and monitoring costs. Profitability depends on matching production scale to market value, reducing downtime with redundancy and strong maintenance and accessing value chains that reward freshness and local production (e.g., urban markets, restaurants, specialty supply). Investors and operators who succeed usually combine conservative engineering margins, realistic

timelines for biological stabilization and diversified revenue streams (hatchery services, live-fish sales, value-added processing). Many recent analyses stress that improving average operational efficiencies rather than chasing theoretical best-case metrics drives the economics forward.

### Environmental and social benefits

When run well, RAS concentrates pollutants so they can be managed, reduces freshwater withdrawals and minimizes escapes, pathogen transfer and interaction with wild population's advantages that favour siting near urban centres and integrated food systems. On the caveat side, energy demand, chemical use (for pH control or disinfection) and the challenge of managing concentrated waste streams must be acknowledged and mitigated. Socially, RAS can create skilled jobs and shorten supply chains; however, equitable access to capital and technical training is essential so that benefits aren't captured only by deep-pocketed industrial players. In short: RAS can be part of a sustainable seafood future, but sustainability depends on local realities and explicit design choices.

### Practical operational checklist

1. Run a matched design study: match species, growth targets and feed plans to bio-filter and solids-removal sizing.
2. Prioritize redundancy: backup pumps, dual oxygen sources and alarmed telemetry.
3. Adopt sensor-based monitoring with conservative alarm thresholds.
4. Invest in staff training on a practical SOP (start-up cycling, emergency aeration, solids removal).
5. Pilot energy-reduction measures (gravity flows, high-efficiency pumps, waste-heat recovery).

**Table: RAS components, functions and practical tips**

S.no.	Component / Consideration	Primary function	Practical tip
1	Culture tanks	Hold and grow fish	Round tanks reduce dead zones; avoid sharp corners
2	Drum filter / mechanical filter	Remove coarse and medium solids	Size for peak feed load, not average
3	Sand filter / micro screen	Fine solids polishing	Easy backwash is essential for labour savings
4	Bio-filter (nitrifying)	Convert $\text{NH}_3 \rightarrow \text{NO}_2 \rightarrow \text{NO}_3$	Overbuild capacity for safe margins
5	Denitrification / polishing	Remove accumulated nitrate	Consider hybrid plant/microalgae polishing
6	Protein skimmer / foam fractionator	Remove dissolved organics	Valuable in marine or high-organic loads

7	Oxygenation (diffusers / LOX)	Maintain dissolved oxygen	LOX for high-density bursts; diffusers for steady flow
8	Degassing unit	Remove CO <sub>2</sub> and gas super saturation	Place upstream of culture tanks
9	Heaters / heat exchangers	Temperature control	Recover heat from outgoing water where possible
10	UV / ozone / chlorination	Disinfection	Use carefully to avoid toxic by-products
11	pH and alkalinity control	Buffer water chemistry	Monitor alkalinity often nitrification consumes alkalinity
12	Pumps and piping	Circulate water	Use variable speed drives; plan for redundancy
13	Sensors & PLC / SCADA	Real-time monitoring & control	Alarms should notify staff and trigger auto-safeguards
14	Backup power / generator	Emergency uptime	Sized for life-support loads, not whole facility
15	Feed management systems	Accurate feed delivery	Overfeeding is the largest controllable waste source
16	Quarantine / biosecurity station	Isolate new stock and prevent disease	Simple footbaths and dedicated gear reduce risks
17	Waste sludge handling	Dewatering and disposal	Compost or co-digest where regulations and markets allow
18	Water-makeup & exchange	Control salinity and nitrate	Minimize but maintain a controlled exchange plan
19	Animal welfare protocols	Health checks and humane handling	Train staff in early disease detection
20	Energy efficiency measures	Reduce kWh/kg production	Incorporate heat recovery and optimized hydraulics

### Pathways for scaling and innovation

Scaling a RAS operation successfully is rarely a matter of simply building larger tanks. It often requires modular growth replicate proven blocks, automate predictable tasks and retain manual oversight for biological decisions. Innovation areas with near-term promise include improved media for bio-filters that shorten start-up time, integrated algae/microgreen modules that turn nitrate into value-added products and smarter control algorithms that reduce energy by adapting flow and aeration to live load. Public-sector hatcheries and university partnerships can lower the barrier for small and medium enterprises to test new approaches before heavy capital commitment.

### Conclusion

Recirculatory Aquaculture Systems are a pragmatic path toward more controlled, water-efficient and bio secure seafood production especially when food is needed close to population centers or when environmental constraints preclude extensive pond expansion.

They are not a universal solution: the economics and environmental balance depend on species, local energy prices, access to markets and managerial capacity. The systems that perform best marry conservative engineering margins with clear business models, invest in energy and heat recovery and treat biological stability as a continuous operational discipline rather than an engineering checkbox. For practitioners, the message is straightforward: design for resilience (redundancy, monitoring, staged solids and nitrogen removal), start modest and scale in modules and keep the operational learning curve explicit in budgets and timelines. When these principles are followed, RAS can be a durable, sustainable tool to deliver fresh, high-quality fish with a smaller water footprint and stronger biosecurity than many conventional systems.

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