ENGINEERING SUBJECT MATTER NOTE

Engineering Controlled Aquaculture

An investigation into the hydraulics, stoichiometry, and failure containment of Recirculating Aquaculture Systems (RAS) in water-scarce African corridors.

Abstract

Recirculating aquaculture systems, or RAS, are intensive water-reuse production platforms in which fish tanks are coupled to solids removal, biofiltration, gas-transfer equipment, disinfection, thermal control, and automation so that the same process water can be reused many times. Intensive indoor RAS can operate at about 300 liters of new water per kilogram of fish produced, and with denitrification plus phosphorus removal that can fall to roughly 30-40 L/kg; the comparative flow-through trout example uses about 30 m3/kg.

The engineering attraction of RAS is control. It can stabilize temperature, dissolved oxygen, pH, and water quality; reduce dependence on external water bodies; and support production close to market. The engineering penalty is equally real: energy use can range from 2.9 to 81.5 kWh/kg fish, capital cost often accounts for 23-57 percent of total cost, and a serious design or operating failure can kill stock in minutes rather than days.

System Architecture

A working RAS is not a tank with a filter attached. It is a linked hydraulic-biological plant. The core water path is typically fish tank to solids capture to biofilter to degassing to oxygenation to disinfection to pump or sump and then back to the production tanks. Modern systems often add side-loops for denitrification, sludge thickening and dewatering, alkalinity dosing, temperature management, reject-water treatment, and emergency oxygen supply.

The most important architectural decision is how far the system pushes recirculation intensity, because lower make-up water increases both the strategic value and the treatment burden of the plant. A more intensive loop reduces freshwater abstraction and makes nutrient capture easier, but it also makes the farm more dependent on filtration, gas management, chemical dosing, and operator response.

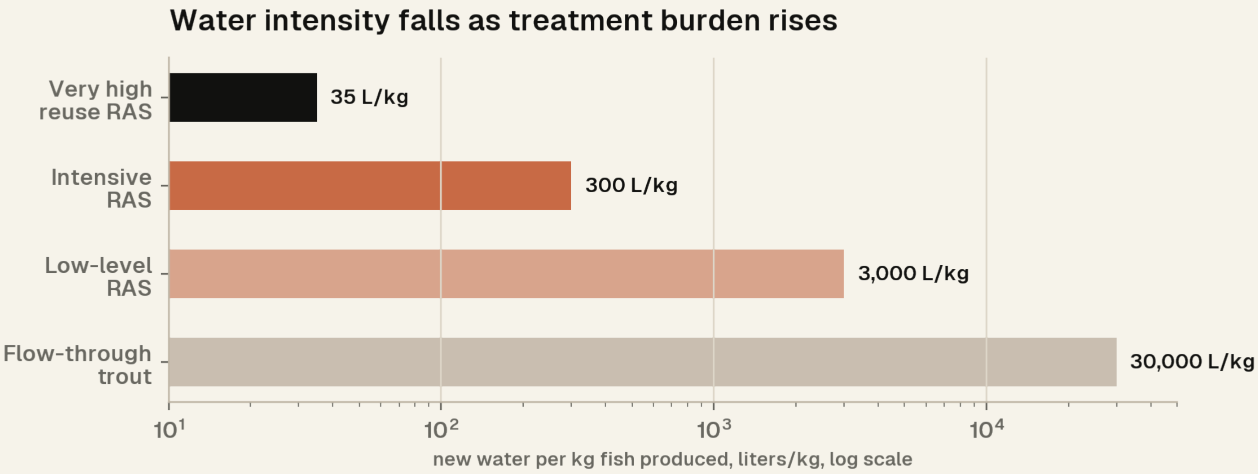

Figure 1. FAO theoretical comparison for a 500-tonne/year trout system. The design question is not only water saved, but treatment burden created.

System type	New water use per kg fish	Daily new water as share of system volume	Degree of recirculation
Flow-through trout example	30 m3/kg	1,028%	0%
Low-level RAS	3 m3/kg	103%	95.9%
Intensive RAS	0.3 m3/kg	10%	99.6%
Very high reuse RAS with N and P removal	0.03 m3/kg	1%	99.96%

FAO theoretical comparison for a 500-tonne/year trout system with 4,000 m3 total water volume.

Mass Balance and Core Components

The architecture determines the waste profile. In FAO's worked mass-balance example, 100 kg of feed containing 7.2 kg nitrogen and 1.0 kg phosphorus yields 91 kg of fish growth at FCR 1.1, but it still leaves dissolved and particulate nitrogen and phosphorus in wastes. RAS is a concentration-and-control technology, not a waste-erasing technology.

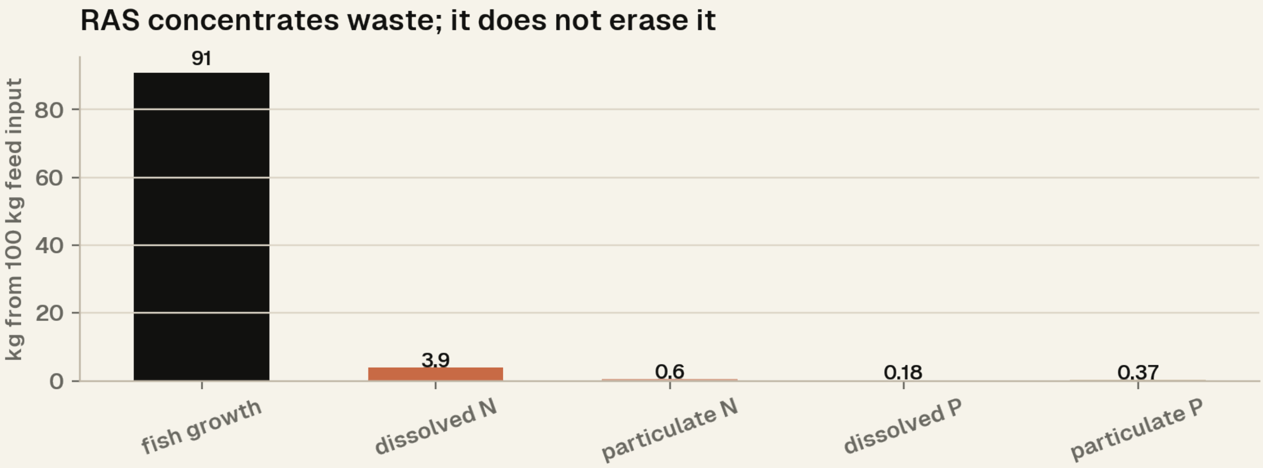

Figure 2. Simplified mass-balance framing from a 100 kg feed input example. The output is not only fish growth; it is also a concentrated waste-management obligation.

The first unit operation is solids management. About half of feed consumed is excreted as solids. Particulate organic matter carries roughly 10-30 percent of total nitrogen and 30-80 percent of total phosphorus. Solids are also biological: they support heterotrophic bacterial growth, increase fish stress, and worsen water clarity and pathogen pressure.

The second unit operation is biofiltration. The core reaction is nitrification: ammonium is oxidized to nitrite and then nitrate. Each gram of ammonia-nitrogen oxidized to nitrate consumes about 4.57 g oxygen and 7.14 g alkalinity as CaCO3. Biofilters therefore do not just remove ammonia. They consume oxygen, push pH downward, and force continuous alkalinity management.

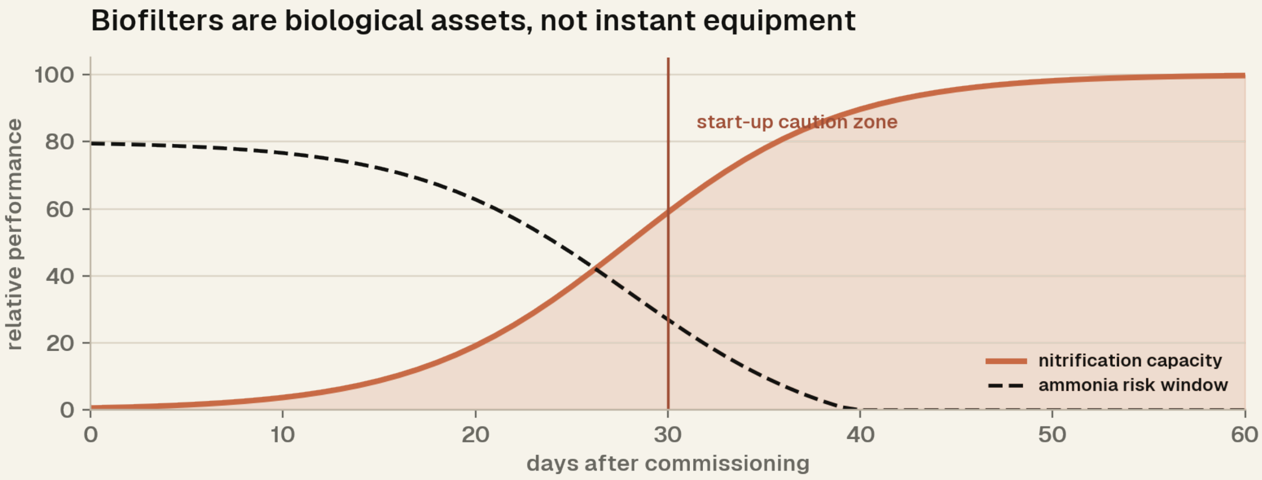

Figure 3. New biofilters are biological systems. Pushing feed before nitrification capacity is established is an operating error, not a technology problem.

Gas, Disinfection, and Monitoring

Gas management is where many non-specialists underestimate RAS complexity. After the fish tanks, water oxygen saturation may fall to about 70-80 percent; ordinary aeration typically restores it to around 90 percent. If inlet water above air saturation is required, pure oxygen is needed. The catch is carbon dioxide: pure oxygen transfer does not remove CO_2, so an oxygen-delivery system has to be paired with an equally serious degassing strategy.

Disinfection and polishing come after the basic mass-balance work is under control. UV works best at high ultraviolet transmission, and FAO recommends UVT of 90 percent or more for strong kill performance. Ozone can add major value as an oxidant and water-polishing step, but overdosing can injure fish and harm workers, so ventilation, monitoring, and dosing control are not optional.

Variable	Common operating target or warning point	Systems meaning
Dissolved oxygen	>60% saturation; often >5 mg/L for warmwater fish	Protects fish growth and keeps nitrifiers working efficiently
Carbon dioxide	Usually kept <20 mg/L; poor designs can climb to 50-100 mg/L	High CO_2 depresses pH, hurts biofilter performance, and increases fish stress
pH	Common operating balance around 7.0-7.5	Lower pH reduces NH_3 toxicity but can slow nitrification
Alkalinity	Often managed around 70-200 mg/L as $CaCO_3$	Buffers pH and supports nitrification
Nitrite-N	Often kept below 0.5 mg/L	Brown-blood risk and chronic production loss
UV transmission	About 90% or more for efficient UV disinfection	Determines whether installed UV dose is actually useful

Representative values compiled from SRAC warmwater operating guidance, FAO's RAS guide, and recent review literature.

Efficiency, Tradeoffs, and Failure Modes

The strongest case for RAS is not that it is universally better than ponds, cages, or raceways. It is that it changes the engineering envelope of aquaculture. RAS can use 90-99 percent less water and less than 1 percent of the land area of conventional systems. This is valuable where land is expensive, intake water is unreliable, or a farm needs to be close to customers.

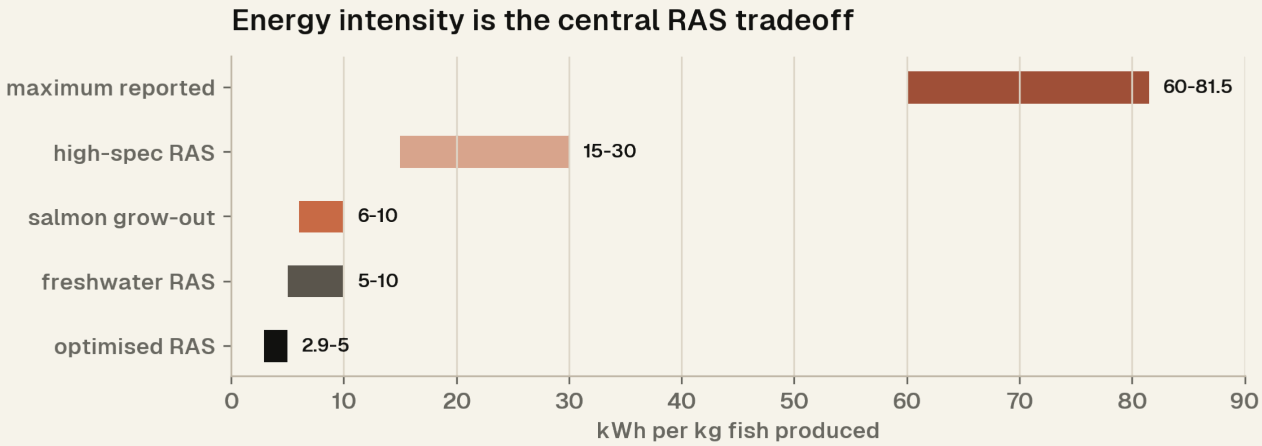

Figure 4. Energy intensity spans a wide range. RAS sustainability depends heavily on energy source, system design, and thermal control.

RAS failures are usually chain failures. One weak link can cascade into the next because hydraulics, chemistry, biology, and fish welfare are tightly coupled. Power outages, hydraulic fouling, solids accumulation, biofilter immaturity, gas-management imbalance, hazardous byproducts, and poor start-up sequencing all require explicit engineering responses.

Failure point	Typical consequence	Engineering response
Power outage	Dissolved oxygen can fall to stressful levels in minutes	Automatic transfer, backup generator, alarms, oxygen solenoid backup
Hydraulic fouling	Flow drops, aeration efficiency falls, biofilter performance declines	Oversized pipes, accessible cleaning points, routine inspection
Solids accumulation	More heterotrophic growth, poorer nitrification, fish stress	Fast solids capture, microscreen discipline, polishing for fines
Biofilter immaturity	Ammonia and nitrite spikes during start-up	Staged loading, seeding, pH and alkalinity control

Kenya and Africa

The regional argument for RAS starts with constraint, not novelty. Kenya's renewable internal freshwater resources per capita fell from 904.2 m3 in 1990 to 381.5 m3 in 2022. Below 1,000 m3/capita/year is commonly treated as water-scarce territory. Kenya is not just water-stressed; it is deep into water-scarce territory.

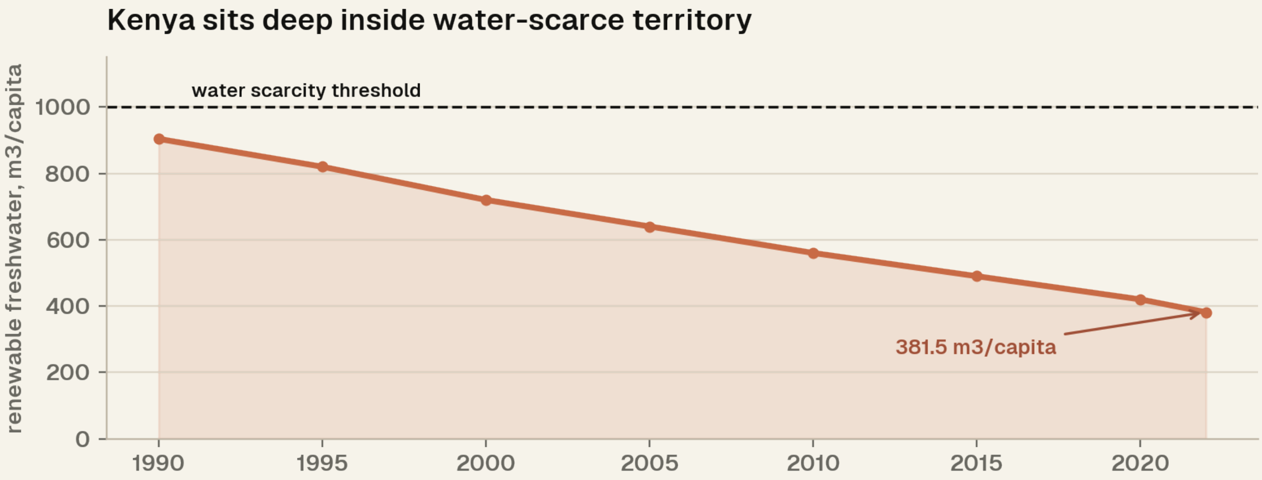

Figure 5. Kenya renewable freshwater per capita. Controlled systems become more compelling where water, land, biosecurity, and market proximity matter together.

At the continental level, Africa produced 13.1 million tonnes of fisheries and aquaculture output in 2022, of which 2.5 million tonnes came from aquaculture. That aquaculture volume is only about 1.9 percent of world aquaculture production, but it has grown by 455 percent since 2000, the fastest regional growth rate in the world.

Regional indicator	Latest figure	Why it matters
Africa fisheries + aquaculture output	13.1 million tonnes in 2022	Large sector, still modest relative to population
Africa aquaculture output	2.5 million tonnes in 2022	Small base compared with other regions
Africa aquaculture growth since 2000	+455%	Fast growth proves demand and policy momentum
Africa aquatic-food consumption	9.4 kg/capita	Lowest regional average globally
Kenya total fish output	168,424 MT in 2024	National market is large enough to matter
Kenya cage-culture share	76.4% of aquaculture	Existing sector is cage-led, not land-system-led
Kenya freshwater resources	381.5 m3/capita in 2022	Strong structural case for water-efficient systems

Technical Interpretation

For a city-market case such as Nairobi and the surrounding Kiambu/Juja corridor, the reasonable conclusion is not that full-scale RAS automatically beats ponds or cages. The better inference is narrower: where Kenya needs biosecure hatchery or nursery output, controlled broodstock, stable peri-urban fresh supply, or aquaculture in locations constrained by water or land, RAS becomes strategically attractive.

The serious RAS story is modular loops, measured mass balance, oxygen and power redundancy, reject-water and sludge handling, and disciplined control of DO, CO2, pH, alkalinity, ammonia, nitrite, nitrate, and solids.

It is not enough to claim 95-99 percent water reuse without showing what happens to concentrated waste, how the plant survives a blackout, or how the energy system closes. In Kenya and Africa, where water constraints are real and market growth is visible, that distinction is exactly what separates a serious RAS proposal from a marketing deck.

Aqualabs Research | April 2026
Data Sources: FAO RAS Guide, SRAC 2024, World Bank Kenya Profiles.