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ISSUES OF INTENSIVE RECIRCULATING AQUACULTURE SYSTEMS (RAS)

Review of current literature

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We will incorporate new information into subsequent versions of these resources. Some of this research may alter our understanding on current established practice.

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Introduction

Farmed fish are reared in a variety of systems, differing in location (on land or in natural bodies of water), intensity, feed input, water use (circulation and degree of water reuse), and levels of biosecurity, among other defining characteristics. The type of system used also depends on the species (defined by their biological requirements), life stage (with systems providing higher biosecurity favoured for early life stages) and economic feasibility.

Nowadays, the grow-out production phase (to final market size) of most aquaculture species takes place in floating cages, raceways or tanks, or ponds, but there is growing momentum within the industry towards implementing land-based systems with significantly higher densities and water reuse: recirculating aquaculture systems (RAS). RAS have been promoted as solutions to certain environmental problems affecting traditional aquaculture systems, including geographical restrictions, water use, land use, biosecurity and effluent management[1,2]. However, the evidence supporting these benefits is conflicting. There are also serious concerns raised about the welfare of fish kept in these systems, given the highly intensive and barren conditions.

The welfare of any farmed animal can only be as good as is allowed by the characteristics intrinsic to the farming system, i.e. the systems welfare potential[3]. The welfare potential of RAS systems needs to be assessed on a species-specific basis, holistically, taking into account mental wellbeing and expression of natural behaviours.

A variety of aquaculture species have been reared at the grow-out stage in RAS, with the production of some already commercially established and that of others still at an earlier/experimental stage of development. The commercial success of these operations depends on the economic value (market price) and the biological characteristics (growth performance in RAS) of the species[2]. However, behavioural needs and the potential to experience good welfare within the farming environment, which is generally barren due to functional requirements and the need to maintain hygiene and biosecurity, are not usually considered.

The vulnerability of young fish makes biosecurity and environmental control particularly advantageous for maximising survival at the hatchery and juvenile stages, meaning that the use of RAS for hatchery production is widespread. The higher profit margins received for juvenile fish also mean that production is not driven as intensively as for the grow-out stages.

This document reviews the vulnerabilities and challenges faced by RAS in terms of welfare and sustainability and outlines the concerns that CIWF has with this form of production, particularly when used for the grow-out phase of species whose biological and behavioural needs are unlikely to be met.

The scientific literature available on this topic is heavily focussed on salmon production. Although some welfare impacts may be species specific, many are consequences of the functioning of the system itself and therefore will impact welfare similarly. The welfare potential of less intensive lower trophic forms of RAS should be given consideration.

What is a Recirculating Aquaculture System (RAS)?

Recirculating Aquaculture Systems (RAS) are production systems used to rear aquatic animals based on passing water through a circuit of filtration and treatment components, which restore the water quality sufficiently for it to be returned to the rearing tanks and reused. New water is still required to replace water lost through evaporation or extracted to remove waste, however, the recirculated flow is generally between 90 and 99% of the total flow[1,4], with some authors suggesting 95.9% as the minimum[2].

The small proportion of water which is not recirculated, and requires replacement, is discharged through various processes in RAS, such as removal of solids, cleaning procedures, husbandry and transport procedures, and drainage of circuits at the end of a production cycle. Wastewater containing solid waste, i.e. from drum filters, is normally the major wastewater stream. This is generally subjected to further filtration and sedimentation processes leaving a concentrated sludge for removal by truck, and a water free of solid matter, for discharge, or in some cases, recirculation back into the system. Where and how final discarded water is discharged will depend on farm location and regulations that aim to maintain the water quality of the area.

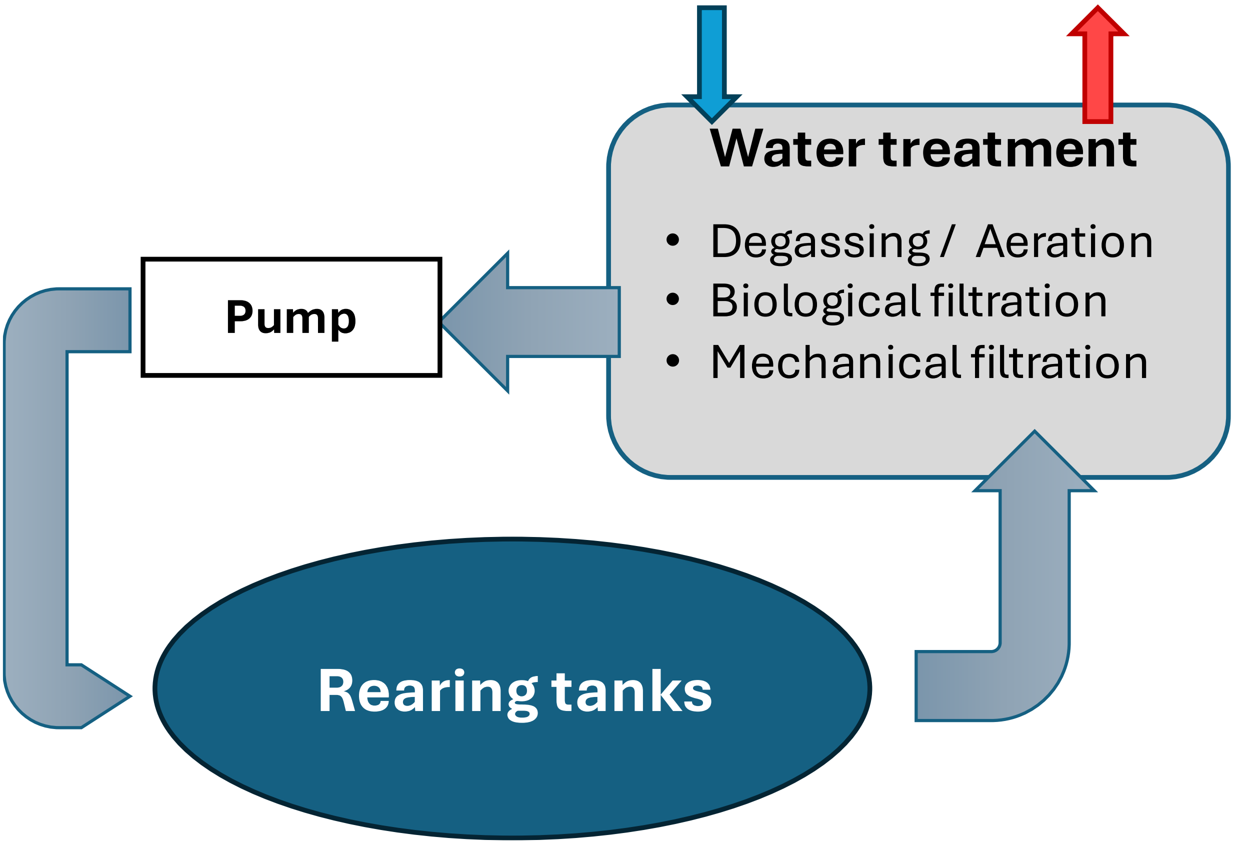

Figure 1: Basic scheme of a RAS system. Grey arrows indicate the main water circuit. The blue arrow represents the new water income and red arrow represent the discharge of wastewater and sludge.

Typically, water is pumped from a collection tank (sump) at the lowest point in the system to the rearing tanks via oxygenation and disinfection units, if these are present (not all systems utilise them). The water then flows from the rearing tanks through the rest of the circuit and the water treatment steps by gravity. The basic design (Figure 1) of a RAS has been conservative over time, but each system design shows variances based on need and expertise of designers and management staff. Additional components are often included in RAS, such as oxygenation chambers supplying pure oxygen, heating and cooling elements for temperature control, ultraviolet or ozone disinfection components. The main feature of RAS - the **capacity of restoring water quality to appropriate parameters** - is achieved by passing the water through the treatment circuit at a sufficient flow rate. The three main steps or subsystems in the treatment circuit in their most basic form are:

- Mechanical filtration: removal of particulate waste matter to leave the water physically clean.
- Biological filtration: use of bacteria to process harmful nitrogen products.

- Degassing and aeration: removal of harmful gases such as carbon dioxide, nitrogen gas or hydrogen sulphide, and addition of oxygen, if needed through aeration and/or injection of oxygen into the water.

The growth of the RAS industry has generally been based on the use of technology, and the intensification of production facilitated by increasingly complex treatment systems. However, the principle of recirculation can be applied to a wide range of farming systems by a variety of methods to perform the same role, such as constructed wetlands, including those which are less intensive, and with a greater degree of integration of aquatic animals from lower trophic levels, algae or plants[5,6,7] such as in multi-trophic and aquaponic systems.

The complete control over environmental parameters that is theoretically possible in RAS makes the rearing of any species of aquatic animal theoretically possible. However, many species are particularly poorly suited, physiologically, behaviourally, and/or economically to being farmed in RAS.

This document describes potential issues with RAS as an intensive production system. It is important to note that from a welfare perspective, the impact on different species will depend on their biological and behavioural needs and tolerance to the rearing conditions. As such, the welfare potential of a RAS may differ between species, for example, tuna and shrimp.

Potential issues

Stocking Density

Significantly higher stocking densities are used in RAS than in open systems like cages, or closed systems with less filtering capacity such as ponds. This is due to the increased biological carrying capacity of RAS[8], and the need for profitability[9] in such a high tech system. For example, salmon in open cages are generally reared at maximum densities between 15 and 25 kg/m^3 while in RAS systems the minimum density that is economically viable is between 50 kg/m^3 to 80 kg/m^3[3,9].

Building a recirculation system demands a very high initial investment which, on average, will require a period of 8 years to recover[1]. Additionally, RAS systems incur much larger operational costs than regular farms, principally due to the higher energy demand required to circulate water and operate subsystems. Efforts to reduce the time to recover initial investments and operational costs, leads operators to push for greater output via intensification and higher stocking densities[9].

The pressure to intensify production increases for grow-out of large market-size species that have longer production cycles, increased cost[2], and tighter profit margins. This further exacerbates risks to health, technical failures and loss of stock, which further increases the pressure to intensify production.

Increasing stocking densities generally presents greater risks to animal welfare. There is a misconception that high stocking density only negatively impacts the welfare of farmed aquatic animals through reducing water quality, and that in RAS, where water quality is properly maintained, high stocking densities do not impact welfare. However, there is abundant evidence that welfare is impacted by stocking density independently from its effect on water quality; high densities have been found to increase stress indicators[10,11,12,13], to impair growth,[14,15] appetite[16] and digestion[15], and to increase fin damage[17]. Stress responses to other husbandry procedures such as crowding are also potentially increased[13], as well as aggression and cannibalism in some species e.g. tuna and octopus[18, 19].

Technical Failure

RAS rely on interdependent components to maintain water quality and recirculate the water through the rearing enclosure. While the level of technology of a system does not need to be high, most RAS projects undertaken by high-profile aquaculture companies feature high-tech components, which in turn require access to a reliable power source.

There are multiple critical points of failure in a RAS. Of these, failure of either the power supply, solids filters, degassing chambers, or oxygenation equipment are all likely to cause rapid mass mortality due to asphyxiation. The interdependence of the proper functioning of system components makes such systems inherently vulnerable to failure.

The first phase of water treatment is invariably the removal of solid wastes by mechanical filtration, and the efficacy of all further downstream treatment processes depend on the success of this process. Solid wastes in RAS leach phosphorus, organic carbon and ammonia (ammonia), which degrades the water quality[20]. The proliferation of respiring bacteria growing on the surface of the particles leads to higher oxygen demand, and higher carbon dioxide levels[21]. Suspended solids also impact biofiltration downstream by clogging the biomedia[22] and promoting the growth of unwanted competitive heterotrophic bacteria[23]. Pathogenic bacteria may also proliferate on the surface of suspended solids[24,25], and ozone and UV disinfection is hindered by the presence of suspended solid particles[26,27]. Drum filters are the technological equipment typically employed for this and are reported to be a typical point of system failure[28].

Badiola et al. (2012) investigated, by way of a survey that included several companies operating RAS, the major technological issues that were faced. Unfortunately, there does not appear to be a more recent source of the kind of information in this survey available, however, despite its age it continues to be valid. The report found that ammonia, nitrite (nitrite), oxygen, carbon dioxide, and suspended solids levels were challenging to control consistently. The management of biofilters and solids removal units was cited as being problematic for most operators. The impact of suspended solids on the system, particularly in terms of their impact on biofilters, which were often undersized, was reported by most respondents as a commonplace issue. A further theme was the lack of expertise in both the management and the initial design of the systems, which was a particular issue when the designers were not the final operators. Poor design involving overly optimistic assumptions to cut costs at the investment stage was cited as leading to operational problems, where components were undersized, or of suboptimal quality or improper specification, and where back-up systems or components were not provided.

As mass mortality events sometimes occur in cage farming, one of the major claimed advantages of RAS is the ability to avoid such events through complete environmental control; however, the events described in Table 1 demonstrate the vulnerability of aquatic animals to a multitude of potential points of failure in intensive RAS farms. **Technical failure can easily lead to mass mortality, with huge numbers of fish suffering slow and painful deaths from asphyxiation, carbon dioxide poisoning or ammonia poisoning.** Where technical failure is less sudden, poor conditions may still force emergency (or earlier than initially planned) harvests, and these conditions are likely to cause chronic stress and poor welfare.

Table 1: Summary of publications describing RAS failures that caused high mortality or reduced fish welfare.

Species	Country	Year	Issue	Cause
Salmon	Denmark	2020	Mortality of 227,000 fish[29]	High nitrogen levels due to unknown issue.
		2021	Mortality of 400 tons of near harvest sized fish[30]	Stagnant water exposure due to human error
		2021	Mortality of all remaining stock[31]	Fire, cause unknown.
	USA	2021	Mortality of 500,000 fish[32]	Fouling of biofilters and trickling filters with solids
		2022	Elevated mortality and emergency harvesting[33]	Unknown
		2024	Harvesting of undersized fish[34]	Failed growth forecasts and environmental conditions
	Canada	2023	Mortality of 100,000 fish[35]	Collapse of degassing unit
	Japan	2025	Mortality of 170,000 fish[36]	Asphyxia due to circulation stopping caused by automation and human error
Salmon smolts	Norway	2023	Mortality of 1.9 million fish[37]	Unknown
		2024	Mortality of 500,000 fish[38]	Water quality issue
Salmon post-smolts	Japan	2024	Mortality of 50,000 fish[39]	Unstable foundations caused tank breakage
Arctic charr	Canada	2023	Mortality of 100,000 fish[40]	Asphyxia from main and back-up power failure

Water quality and flow, and biosecurity

The welfare of aquatic animals is highly dependent on the quality of the water they live in. Temperature, suspended solids, oxygen and carbon dioxide levels, ammonia, nitrite and nitrate levels are of critical importance to welfare as they have a direct influence on health and physiological functioning. Aquatic animals can only thrive physically in water in which parameters remain within certain thresholds.

In RAS, most suspended solids are organic in origin, comprised of faeces, feed, and bacterial biomass[41,42]. Most of the negative impacts of suspended solids on fish welfare in RAS are indirect, harming the fish through their impact on the functioning of other critical water treatment processes. However, excessive turbidity caused by suspended solids reduces visibility, which can lead to reduced feeding[43,44,45].

Pure oxygen is typically supplied to fish in RAS using specialised equipment. While such systems may be mechanically very reliable, reduced flow of water due to blockages in pipes can reduce the oxygen supply to the fish. In such cases it is typical for alarms linked to oxygen sensors to alert staff, or for automated systems to activate a back-up supply of oxygen. Although prolonged hypoxia may be generally avoided, there is an inherent risk in RAS of exposure to periods of acute hypoxia, which is known to cause stress, and impact immune status[46,47,48].

RAS commonly use pressurized oxygenation systems[49]. There is strong economic incentive for this, as such systems can significantly raise (supersaturate) dissolved oxygen levels, thereby supporting higher stocking densities. However, when oxygen is supplied under pressure, a situation can arise where gas bubbles form within the blood or body tissue of the fish[50,51]. Espmark et al. (2010) found that exposure to oxygen supersaturated water caused increased panic episodes in juvenile Atlantic salmon, which they suggested to be indicative of physiological stress or pain.

Aeration methods, such as trickle filters, air bubbles, or surface agitators, equilibrate the gas composition of water and air, but where pure oxygen is used, a separate "degassing" phase is required to remove carbon dioxide[49]. Safe operation of RAS using pure oxygen therefore requires carbon dioxide as well as oxygen to be monitored, however the technology for this is generally not reliable or available[52,53].

Exposure to sublethal concentrations of carbon dioxide (hypercapnia) suppresses appetite in fish[54]. It has also been associated with nephrocalcinosis, whereby mineral deposits form on the kidney, which can ultimately lead to kidney failure[55]. This has been well documented in salmonids[54] and has also been demonstrated in seabass[56] and spotted wolffish[57]. Hypercapnia has also been shown to impede swim bladder inflation in the larval stages of white grouper[58] and has been associated with cataracts in Atlantic cod[59,60].

The impact of hypercapnia on fish health is exacerbated by simultaneous excess oxygen (hyperoxia)[61]. This is of particular concern for RAS where elevated oxygen levels are common.

Another cause for concern is reduced efficacy of degassing due to elevated carbon dioxide levels within indoor farms, which are often poorly ventilated in the interest of heat conservation[49].

Biofiltration takes place in the biofilter which provides a large surface area upon which nitrifying bacteria live and reproduce. The bacterial colony in the biofilter takes a considerable time to become established (a process called “priming”). During this time, the biofilter is either connected to a fish rearing unit stocked at a very low density[62], or has water, absent of fish, circulated through it with the addition of ammonia[63]. Therefore, each time a biofilter is newly configured, or sterilised requiring subsequent priming, there is strong economic incentive to introduce the fish stock too soon, risking exposure to ammonia and/or nitrite. In RAS most water parameters are subject to constant change which affects nitrification rates, meaning the reduction of ammonia and nitrite is also not always immediate, and the frequent exposure of the fish is likely[64].

Despite larger systems being more stable in terms of water quality, producers tend to operate multiple modules of limited size to facilitate husbandry procedures, and to mitigate against catastrophic economic loss in the event of system failure[28], thus, a degree of fluctuation of water quality parameters is generally a feature in RAS.

The most efficient biofilter designs are those in which the biomedia is moving[65] such as fluidised sand filters or moving bed bioreactors with plastic media. Fluidised sand filters are very complex to design[65], while for moving bed bioreactors, the constant abrasive movement of plastic bio-media is likely to produce microplastic waste[66].

Ammonia is produced as a metabolic waste product by aquatic animals, and is toxic to all vertebrates, causing convulsions, coma and death[67]. As well as neurological dysfunction, sublethal effects of chronic exposure to ammonia include damage and physiological alterations to the gills resulting in compromised ion regulation[68,69,70,71,72]. Ammonia toxicity is also well documented in crustaceans[71].

Nitrite is produced as an intermediate nitrogen component from the oxidation of ammonia, and prior to its further oxidation to nitrate. It is toxic to aquatic organisms because it reduces the oxygen carrying capacity of blood[73]. Further negative impacts include gill lesions and oedema in the skeletal muscles of fish[73]. The toxicity of nitrite is far greater in freshwater than saltwater, as chloride in saltwater competes with nitrite for uptake in the gills [74]. It is important to note that the principal mitigating factor used in RAS management to reduce levels of these toxic metabolites is to reduce feed rate, entailing a further negative impact on welfare.

The final product in the nitrification process is the far less toxic compound nitrate. Nitrate toxicity follows the same mechanism as nitrite toxicity[75]. The reason for its reduced toxicity is due to it having a much lower uptake rate in the gills[76]. High nitrate caused side-swimming behaviour and a 4% increase in mortality in juvenile rainbow trout[77]. Adaptive responses including elevated plasma chloride, haematocrit, and haemoglobin levels and heart rate have also been observed in post-smolt Atlantic salmon[78] and elevated rates of protein catabolism have been observed in pike perch[79]. Nitrate levels exceeding 50mg/l also led to reduced growth, health status, and survival in juvenile turbot[80].

In most RAS systems the accumulation of nitrate, the final product of biofiltration, is only controlled through water exchange[81], therefore nitrate typically accumulates, reaching levels far exceeding anything found in natural bodies of water if not removed by renewing the water in the circuit. While methods to remove nitrate through its conversion to inert nitrogen gas do exist and have been applied to RAS, they are not yet widespread[82].

Flow rate of water through fish tanks in RAS is calculated as the minimum required flow that ensures the maintenance of the controlling water quality parameter (normally oxygen), within acceptable thresholds for fish culture[81]. This is an economic imperative as the chosen flow rate directly determines the energy cost of water pumping. The inherent issue with such an approach is due to the compounding negative impacts of reduced water quality parameters, despite their being within established safety thresholds individually. For example, Sun et al. (2016) found juvenile turbot welfare, growth and survival was significantly improved by increasing flow to rates beyond that which were deemed necessary to ensure the maintenance of all major water quality parameters within established safe thresholds for turbot culture. The selection of flow rate therefore represents an inherent conflict of interests between welfare and profitability. Where system design is inadequate, insufficient flow rates can also cause the settlement of solids within the fish tanks, leading to deterioration of water quality[1].

As RAS are closed systems, it is theoretically possible to isolate the cultured fish from all pathogenic organisms present in natural aquatic environments. To this end it is crucial for intensive RAS systems to adhere to a strict biosecurity protocol[81]. While open farming systems rely on the immune system of the fish, RAS aims for the total exclusion of pathogenic organisms through complete biosecurity. In this way, biosecurity facilitates maximal production despite poor welfare, and consequential reduced immune function resulting from stressful conditions caused by high stocking densities and barren environments. Where complete biosecurity is achieved, there is little economic incentive to consider fish welfare, as the degree to which it influences productivity is greatly reduced.

Despite the theoretical possibility of completely effective biosecurity, and the obvious incentive for producers to implement it in RAS farms, the proliferation of pathogenic organisms including parasites, bacteria, fungi and viruses is well documented[26,84,85,86]. Pathogenic organisms may enter a RAS farm via staff (particularly on footwear), via incoming eggs, fry or fingerlings and their transport water, or via infected feed[87]. Once a pathogenic organism becomes established, the organically enriched water in RAS often favours its proliferation[88]. Furthermore, compromised immunity of the cultured animals due to stress is conducive to the rapid and severe infection of the population.

The treatment options are also limited in RAS; chemical treatments are problematic as they are likely to harm the bacterial colony in the biofilters[26]. Ozone treatment and UV radiation of the water are treatments often employed for pathogen control, however, ozone treatment dosage is very complex to calculate and byproducts and residual levels are harmful to fish[26], and UV radiation has limited ability to completely destroy bacteria, and its efficacy is compromised by the presence of particulate matter[27,88]. A further complication is posed by the potential for pathogenic microbes to reside in the biofilm in significant numbers in biofilters, causing recurrent infections[84].

A problematic issue regarding biosecurity that has been reported in RAS is the escape of fish from tanks via entering water inlet pipes. Fish have been reported to enter pipework, and even filters and oxygenation chambers, where they are able to survive, and potentially act as disease vectors, thereby impacting the welfare of subsequent batches as well as suffering confinement and isolation themselves[89].

To summarise, water quality parameters in RAS are highly interdependent, and tend to fluctuate, impacting welfare. The maintenance of water quality parameters within good thresholds is a delicate balance which requires the continuous functioning of all the treatment components involved and is therefore highly vulnerable to failure. Flow rate represents a significant proportion of cost of production, meaning there is a strong economic incentive to operate at the minimum level required, which increases the risk of poor water quality. Finally, the health of the animals is highly dependent on biosecurity, which serves to facilitate growth and production despite stressful rearing conditions, and puts the animals at severe risk of virulent infection when breached.

Rearing environment

The expression of natural behaviours is a key component of good welfare for any animal. How much an animal in captivity is able to express such behaviours is determined by its surrounding environment and the opportunities that this provides. Where captive environments most mimic the natural environment, an animal typically inhabits in the wild, the greater the opportunity to express natural behaviours. RAS typically utilise circular tanks because of their enhanced self-cleaning characteristics compared to tanks of other shapes[49]. This is because water injected into circular tanks tangentially at pressure travels round the tanks creating a spiralling vortex motion, which concentrates settleable solids at the centre of the floor of the tank (provided that it is smooth) where a drainage point is located[49,81].

Smooth bottomed circular tanks such as those used in RAS are ultimately barren environments devoid of structural complexity. Barren environments have been linked with poor welfare in aquaculture. The absence of structures or substrate in the rearing environment has been shown to be chronically stressful and to result in increased aggression, stress response, and reduced immune function and growth rates[89,90,91]. Physical enrichment, as any other type of environmental enrichment, should be suited to the species, and their implementation and design should be carefully researched[90]. The design of this enrichment for RAS should also carefully consider relevant points such as hydrodynamics of the rearing space and biosecurity. For example, Huysman et al. (2019) and Crank et al. (2019) found that environmental enrichment in the form of suspended shapes improved the growth of juvenile rainbow trout in circular tanks compared to those kept in control tanks devoid of stimuli. However, both studies also concluded that the presence of the suspended objects interfered with self-cleaning hydrodynamics in the tanks.

In the case of substrates, the presence of sand has been demonstrated to improve the welfare of farmed sole, whereby stress, aggression and susceptibility to disease are reduced[94,95,96] as they can perform their natural behaviour of partially burying themselves in the sand[97]. However, this species is seen as an ideal candidate for, and increasingly produced in RAS, where operational requirements dictate that sand is not provided due to difficulties of maintaining good cleanliness[98,99].

In RAS, continuous noise from pumps and aerators, and irregular noises from operational procedures and the movement of equipment within the farm may cause stress to the fish. Hang et al. (2021) exposed largemouth bass to a level of noise simulating a commercial RAS. They found that feed conversion ratio (FCR) and immune system was negatively affected in the fish exposed to this noise as compared to a control group experiencing quieter ambient noise levels. Experiments exposing fish to playback of both random and continuous anthropogenic noises resulted in elevated stress levels in koi carp[101] and gilthead seabream[102] and impacted larval development in Atlantic cod[103]. However, it appears that the effect of noise on fish varies with acclimation and according to species[104,105].

It is important to note that the potential deleterious effects of noise induced stress can be serious in extreme cases. For example, in 2020, a Miami based salmon RAS farm had to carry out the emergency harvest of 200,000 fish, of which nearly two thirds were too small to be marketed, because the fish were deemed unable to recover from the chronic stress induced by noises of nearby construction work being carried out to complete the facility[106].

Another environmental parameter known to influence welfare in indoor systems such as RAS is the intensity and regime of artificial lighting. Of particular concern is the use of constant light, which has been associated with faster growth in some species, but also causes chronic stress and behavioural alterations through the disruption of circadian rhythms[107,108,109].

Environmental issues

In conventional aquaculture, the production of the feed is the major contributor to greenhouse gas emissions[110]. In RAS however, the energy used for the operation of the farm;

water pumps, air pumps, heating etc, is considerable, and can account for a greater proportion of the environmental impact than the feed[111].

As can be seen in Table 2, the energy consumption, and resultant global warming potential of RAS is significantly higher than farming the same species using conventional methods. In the case of salmon, the difference can be between 2x and 13x higher global warming potential in kg carbon dioxide equivalent for RAS. In the case of tilapia, the difference may up to 5x, for trout it may be between 4x and 6x, and for sea bass and sea bream it may be between 2x and 4x. The significant variation in the extent of increase across studies represents context specific differences, particularly relating to the impacts of electricity generation and whether renewable sources were considered.

Table 2: Carbon emissions for different species in farmed in RAS compared to conventional methods.

Species	Kg carbon dioxide equivalent emission/kg liveweight	
	RAS farmed	Non-RAS farmed
Salmon	7.01	3.39 [112]
	28.2*	2.07 [113]
	16.7	- [111]
	-	2.16 [110]
Tilapia	5.15	- [114]
	-	0.96 - 6.13 [115]
	-	1.52 - 2.1 [116]
	-	2.96 [107]
Trout	13.62	2.24 - 3.56 [118]
	6.1	1.16 [119]
	-	1.18 [120]
Seabass and seabream	9.66 (land based)	2.44 [121]
	7.25 (land based)	3.31 [121]
Cod	21.64	- [122]

* This study compared production of Arctic Charr in RAS to salmon in cages.

One of the aspects of RAS that is cited as an environmental benefit is the reduced land use compared with other forms of land-based aquaculture[81]. While it is clearly true that RAS uses less land than extensive systems operating at much lower stocking densities, the same is not necessarily true of intensive flow-through systems. Compared to a conventional river or spring fed flow-through system, the assertion that RAS has higher production per unit area is based on assumed higher stocking densities. Moreover, the additional infrastructure required in RAS (solids filters, biofilters, degassing chambers, oxygenation units, pumps etc) inevitably occupies additional space.

Often, flow-through systems are converted to RAS to increase production from a limited quantity of water that a company is permitted to use. Similarly, reduced availability of water due to reasons such as climate change may necessitate the conversion to RAS to maintain production at a given level. Such developments inevitably imply spatial expansion and a change of land character, as more infrastructure and buildings for housing equipment are required.

Greatly reduced water use is one of the major cited benefits of RAS[81]. This is certainly true in a sense but comparing RAS to other aquaculture methods regarding water use is not straightforward. In the case of net cage aquaculture, water is not used at all, but degraded with organic waste, and the environmental sustainability of the operation depends on the ability of the surrounding aquatic environment to assimilate the waste. In the case of intensive flow-through systems the water is generally abstracted from a river or spring and returned further downstream, with the sustainability of the system again depending on the ability of the downstream environment to assimilate the organic waste, which is normally somewhat reduced through solids removal filters and settlement reservoirs downstream of the fish tanks.

In this sense, flow through systems have a much greater requirement of water than RAS, but it is borrowed rather than used. In the case of both flow-through and RAS, the water that is truly used, i.e. not returned to the body of water it was taken from, is the water present in discarded waste sludge. There is no inherent reason why flow through systems cannot employ the same technologies used for solids removal as RAS and therefore use just as little water.

Fishmeal and fish oil

One of the economic advantages proposed for RAS for grow out is the ability to produce fresh fish close to market, when wild caught or conventionally farmed fish is inevitably transported long distances, frozen, or with reduced shelf-life[123]. For this reason much of the growth of the RAS industry has been based on high value carnivorous species such as salmon, trout, turbot and seriola[123] which require high levels of fishmeal and fish oil in their feed.

From a welfare perspective, the rearing of carnivorous species on manufactured feeds limits their welfare potential, as they are denied the opportunity to exhibit the hunting behaviours intrinsic to their natural lifestyle. The secondary impact on the welfare of the vast numbers of wild fish, estimated at 490-1,100 billion globally[124], used for feed must also be considered.

The use of wild caught fish for farmed fish feed is inherently unsustainable[124], and responsible for the depletion of wild fish stocks severely impacting marine food webs and biodiversity. In addition, where fishmeal and fish oil is produced from fisheries in developing regions, nutritional and/or economic wealth is removed from people that may rely on these resources for their livelihoods.

Conclusion

RAS requires considerable capital investment and a high operational cost, leading to highly intensive conditions for grow-out production in order to attain acceptable profit margins. High densities have been extensively linked to poor welfare in farmed aquatic animals.

Due to the highly complex interdependent chemical-biological balances at play, water quality fluctuates and is vulnerable to deterioration in the case of poor system functioning and/or technical failure. Accounts of mass mortality as well as emergency/earlier than planned harvests are frequently reported. Enclosure design results in barren rearing environments, which have been extensively linked to higher levels of stress, and poor mental welfare in aquaculture species.

Carbon dioxide emissions per kg produced may be anywhere from 2 to 13 times higher in RAS than for non-RAS farming methods, bringing into question claims regarding their enhanced sustainability. In addition, RAS tends to be used to produce high-value carnivorous species, a practice which is questionable from an environmental, social, and animal welfare perspective.

It is clear that intensive RAS systems severely limit the welfare potential of most aquaculture species. For this reason and those outlined above, **RAS should not be used for the grow-out of high trophic level species with behavioural needs that cannot be met.**

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